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AN APPROACH TO THE DEVELOPMENT OF SOFTWARE FOR COMPUTER-AIDED DESIGN OF SATELLITE COMMUNICATIONS RECEIVERS FOR OPERATION IN SCINTILLATING CHANNELS

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An extensive inventory of techniques to provide robust communications in nuclear-disturbed signal propagation channels has been developed and tested over the past decade. The work described herein is intended to facilitate the process of placing these mitigation techniques in the hands of the designer through the development of a computer-aided design (CAD) software package. To maximize its utility, the CAD software is being developed to run on desktop personal computers (PCs). When developed, this software will allow signal statistical parameters (τ_0, f_0, σ_χ^2, etc.) obtained from Defense Nuclear Agency signal specifications and from Nuclear Criteria Group signal criteria to be readily incorporated in the communications link design process. the PC-based CAD software will enable the designer to input communications system characteristics that may be constrained by other considerations, together with DNA specifications of disturbed signal parameters that the system must be designed to withstand. The CAD software will then provide information on modulation, demodulation, tracking, coding, and diversity requirements to obtain specific

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CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement

MULTIPLY ⟶ TO GET ⟵	BY ⟶ BY ⟵	TO GET DIVIDE
angstrom	1.000000 x E -10	meters (m)
atmosphere (normal)	1.01325 x E +2	kilo pascal (kPa)
bar	1.000000 x E +2	kilo pascal (kPa)
barn	1.000000 x E -28	meter² (m²)
British thermal unit (thermochemical)	1.054350 x E +3	joule (J)
calorie (thermochemical)	4.184000	joule (J)
cal (thermochemical) / cm²	4.184000 x E -2	mega joule/m² (MJ/m²)
curie	3.700000 x E +1	*giga becquerel (GBq)
degree (angle)	1.745329 x E -2	radian (rad)
degree Farenheit	$t_K = (t_F + 459.67)/1.8$	degree kelvin (K)
electron volt	1.60219 x E -19	joule (J)
erg	1.000000 x E -7	joule (J)
erg/second	1.000000 x E -7	watt (W)
foot	3.048000 x E -1	meter (m)
foot-pound-force	1.355818	joule (J)
gallon (U.S. liquid)	3.785412 x E -3	meter³ (m³)
inch	2.540000 x E -2	meter (m)
jerk	1.000000 x E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448222 x E +3	newton (N)
kip/inch² (ksi)	6.894757 x E +3	kilo pascal (kPa)
ktap	1.000000 x E +2	newton-second/m² (N-s/m²)
micron	1.000000 x E -6	meter (m)
mil	[illegible]0000 x E -5	meter (m)
mile (international)	1.609344 x E +3	meter (m)
ounce	2.834952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448222	newton (N)
pound-force inch	1.129848 x E -1	newton-meter (N·m)
pound-force/inch	1.751268 x E +2	newton/meter (N/m)
pound-force/foot²	4.788026 x E -2	kilo pascal (kPa)
pound-force/inch² (psi)	6.894757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535924 x E -1	kilogram (kg)
pound-mass-foot² (moment of inertia)	4.214011 x E -2	kilogram-meter² (kg·m²)
pound-mass/foot³	1.601846 x E +1	kilogram/meter³ (kg/m³)
rad (radiation dose absorbed)	1.000000 x E -2	**Gray (Gy)
roentgen	2.579760 x E -4	coulomb/kilogram (C/kg)
shake	1.000000 x E -8	second (s)
slug	1.459390 x E +1	kilogram (kg)
torr (mm Hg, 0° C)	1.333220 x E -1	kilo pascal (kPa)

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1
INTRODUCTION

1.1 BACKGROUND.

Atmospheric nuclear detonations can produce a variety of disturbances to radio signal propagation. These disturbances include absorption, phase shift, time delay, dispersion, refraction, polarization rotation, multipath, and increased noise levels. In addition, relatively small-scale inhomogeneities in the propagation medium can cause signal scintillations, which are random fluctuations in received signal amplitude, phase, polarization, time-of-arrival, and angle-of-arrival.

Uplinks and downlinks between ground or airborne terminals and satellites, as well as crosslinks between satellites, are likely to suffer such signal disturbances due to propagation through regions of enhanced ionization in nuclear environments. The disturbed regions are particularly widespread and long-lasting following nuclear detonations at high altitudes (above about 100 km). In such high-altitude nuclear environments, satellite links are susceptible to potentially severe signal scintillations due to widespread and long-lasting regions of field-aligned ionization structure, known as striations.

Thus, in addition to the ever-present jamming threat, satellite systems must also contend with signal scintillation disturbances if the system is to operate in a nuclear environment. If a communications system is not specifically designed to operate in the presence of signal scintillation, system performance will most likely be severely degraded when scintillation is encountered. However, performance degradation can be substantially reduced, or mitigated, if the characteristics of the disturbed propagation path, or channel, are properly accounted for in the design of the communications equipment.

The fact that mitigation of signal scintillation, or fading, is possible can be readily understood when one realizes that scintillation *per se* does not reduce the average signal energy below the level received in an otherwise identical nonfading channel. The signal energy is just redistributed in time and possibly in time-of-arrival and angle-of-arrival.

If a communications link is designed to be relatively insensitive to such redistribution of signal energy, there is no fundamental reason why the link cannot be made to work essentially as well in fading channels as in a nonfading additive white Gaussian noise (AWGN) channel. Indeed, practical designs with performance in fading channels closely approaching that in nonfading channels have been developed.

Figure 1 illustrates the nature of the problems and solutions that provide the motivation for the work described in this report. This figure is cast in terms of the

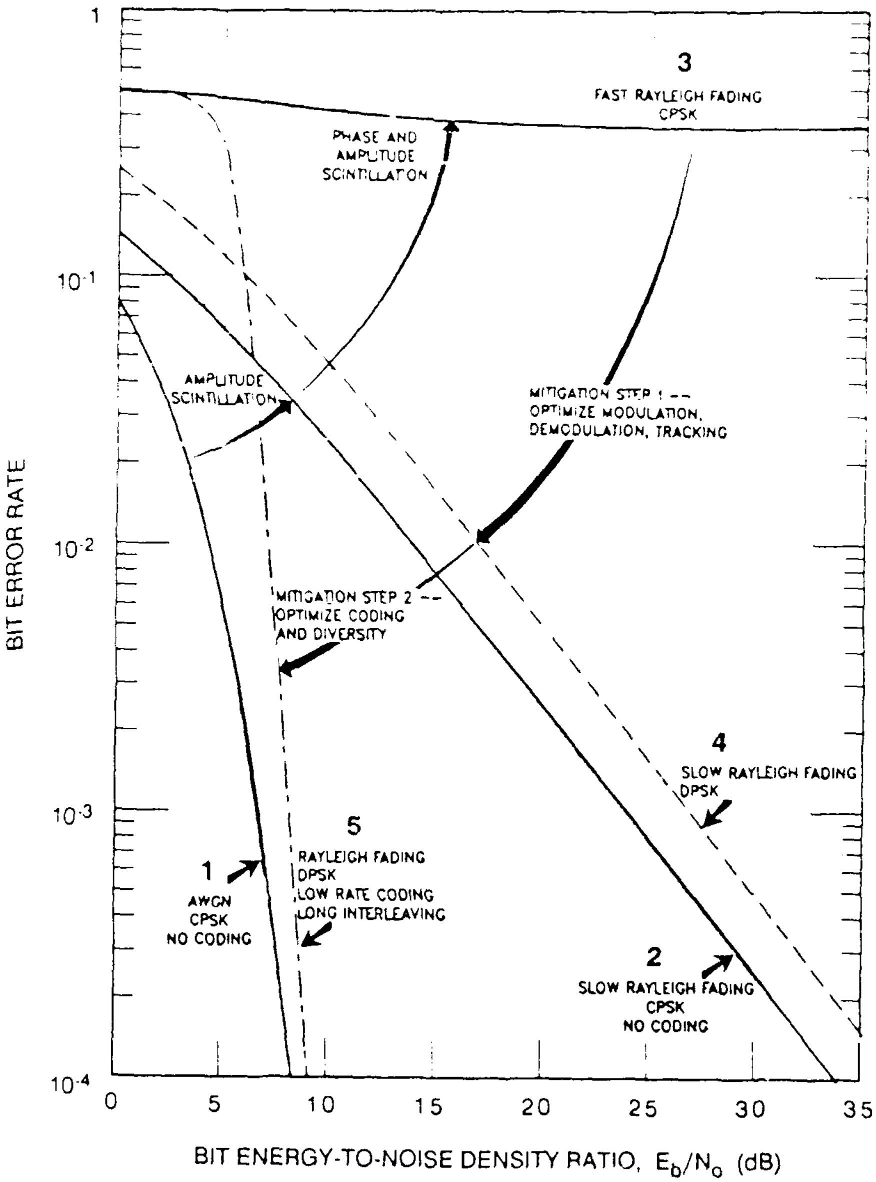

Figure 1. Steps involved in scintillation mitigation.

probability of binary error, or bit error rate (BER), as a function of the received signal-to-noise ratio, measured in terms of the ratio of energy per bit (E_b) to the one-sided spectral density of the additive white Gaussian noise (N_0). While not completely descriptive of link performance in the presence of signal fading and interference, such BER curves are commonly used as performance measures for digital links. When the value of E_b/N_0 is interpreted to be the mean value (*i.e.*, the ratio of the *average* signal energy to noise density), the curves are useful as long as one keeps in mind the fact that the error rates are also statistical averages.

Now consider the five curves in Figure 1 in the order in which they are numbered. The first curve shows the performance of an uncoded link operating in the benign AWGN channel. Coherent phase shift keying (CPSK) is used as the example since it is the optimum binary signaling strategy in AWGN. Curve 1 shows the typical exponential decrease of bit error rate with increasing signal-to-noise ratio in the nonfading channel. Curve 2 shows that signal amplitude fading causes the error rate to decrease much less rapidly with increasing signal strength. The resulting inverse dependence on E_b/N_0 would be bad enough, but amplitude fading is always accompanied by phase scintillation. Rapid phase scintillation can cause catastrophic failure of coherent demodulation, as shown in Curve 3. Note that the resulting binary error rate, which approaches the value of 0.5 at which no information is transferred, no longer decreases with increasing signal-to-noise ratio. This unfortunate situation stems from loss of phase coherence in the demodulator, causing signal energy to interfere with itself in coherent processing.

There are two major design steps involved in mitigation of scintillation effects on digital communications links. The first step entails selection of appropriate modulation, demodulation, tracking, and synchronization techniques in the transmitter and receiver equipment so as to remove vulnerability to rapid phase fluctuations in fast fading channels. For example, differentially coherent phase-shift keying (DPSK) does not require carrier phase tracking in the receiver and is therefore less susceptible to phase scintillation. While the simple change from coherent PSK to DPSK is not usually sufficient by itself to eliminate demodulation failure in fast fading, it is one technique that can be used in a mitigated design. When combined with other techniques as discussed by Bogusch [*1987*], the result is virtual elimination of the extreme sensitivity to loss of channel coherence associated with fast fading. Performance then approaches that which can be obtained in the presence of slow amplitude fading (Curve 4).

The second mitigation step involves incorporation of error-correction coding and diversity techniques. This topic is also treated by Bogusch [*1987*], and in numerous references cited therein. In essence, the use of coding and diversity allows the receiver data demodulator to operate at rather high error rates inherent in fading channels and utilizes redundancy in the data stream to correct most of the demodulation errors, thus achieving acceptable overall performance. When these two mitigation steps are properly implemented, link performance will approach that normally expected in a nonfading channel (Curve 5).

Experience has shown that if a communications link is to provide satisfactory performance in a nuclear-disturbed fading channel, it must be designed for that channel. The chances of accidentally obtaining good performance with a link not designed for fading channel communications are slim indeed.

Once nuclear-induced signal propagation disturbances are incorporated into the design process, the probability of success improves dramatically. It is possible to design links that provide good performance over wide ranges of fading conditions. Consequently, if a requirement to operate in a nuclear environment is addressed at the outset of system design, the effort associated with satisfying this requirement should have minimal impact on overall program cost and schedule.

1.2 SCOPE OF EFFORT.

An extensive inventory of practical engineering techniques to provide robust communications in nuclear-disturbed propagation channels has been developed and tested over the past decade. The work described in this report is aimed at facilitating the process of placing these mitigation techniques in the hands of the designer through the development of a computer-aided design (CAD) software package. To maximize its utility, the CAD software is being developed to run on desktop personal computers (PCs).

This software package will allow signal statistical parameters obtained from the *Defense Nuclear Agency (DNA) signal specifications* [Wittwer, *1980*] and from the Nuclear Criteria Group Secretariat satellite link criterion to be readily incorporated in the communications link design process.

When development is complete, the PC-based CAD program will enable the designer to input such parameters as data rate and system characteristics that may be constrained by other considerations, together with DNA specifications of disturbed signal parameters that the system must withstand. The CAD package will then provide information on modulation, demodulation, carrier tracking, error-correction coding and diversity requirements for obtaining specified levels of link performance. Where more than one design option can be used, tradeoff information will be provided. The CAD package will utilize an interactive user interface to facilitate the design procedure.

1.3 PHASE I TECHNICAL OBJECTIVES.

The Phase I work reported here has been directed toward initial development of a software package that will provide an enhanced capability for incorporating scintillation mitigation techniques in the design of digital communications links. The software is intended to facilitate link design so as to ensure successful operation in the presence of signal scintillation and jamming interference. This work will culminate during a subsequent Phase II effort in the development of a CAD package that will provide design options for specified levels of link performance in nuclear-disturbed channels having specified ranges of scintillation parameters.

During this Phase I effort, the feasibility of the basic approach has been established. The specific objectives that have been addressed during the course of this work are as follows:

1. **Algorithm Definition.** Requirements have been defined for algorithms to implement digital communications link design criteria for specified performance levels and specified signal scintillation parameter ranges.

2. **Algorithm Development.** Initial development of algorithms has been carried out to translate performance specifications and signal specifications into design requirements on modulation, coding, and tracking functions.

3. **Processor Definition.** Requirements on host PCs, including processor type, random-access memory (RAM) storage, disk storage, and input/output (I/O) devices, have been identified to implement the CAD algorithms.

4. **User Interface Definition.** User interface requirements have been defined, including menus, windows, on-line help, and graphical outputs, so as to achieve a user-friendly interactive interface.

The following sections of this report present the results of this work. The requirements that have been defined for the CAD software algorithms are discussed in Section 2. Examples of the nature of the algorithms that are being developed, together with a discussion of the architecture envisioned for the CAD program, are also contained in Section 2.

Section 3 provides a discussion and examples of the user interface that has been defined. A monitor screen interface, consisting of both text screens and graphics screens, is being developed. The user will interact with the screen displays by means of a keyboard or a mouse, depending on the hardware configuration of the host machine.

The requirements that have been defined for the host PCs are described in Section 4. The CAD software is being developed for both the IBM PC family of desktop computers, which utilize the Intel 8088/8086/80286/80386 processor chips, and the Macintosh family of computers, which utilize the Motorola 68000/68020/68030 processor chips.

Finally, the conclusions and recommendations that have evolved from this Phase I effort are presented in Section 5.

SECTION 2
ALGORITHM DEFINITION AND DEVELOPMENT

2.1 SOFTWARE ARCHITECTURE.

Before describing the CAD algorithms, it is appropriate to first discuss the overall architecture in which the algorithms will function. The computer program architectural design has an important influence on both the user interface and the efficiency with which the CAD algorithms will operate. Description of the interactive user interface is given in Section 3. As discussed there, the user may specify a communications link in a number of different levels of detail, depending on the degree to which he knows or wishes to constrain the link design. A variety of different waveforms can be chosen, with many different choices available for the modulation, coding, interleaving, and synchronization techniques. The rates at which information passes through the various functional elements of a digital communications link can vary widely, even with the same basic user data rate. This fact alone places an important requirement for flexibility on the CAD program architecture.

Consider, for example, the link layouts shown in Figures 2 and 3. The first layout, Figure 2, is representative of a fairly simple, albeit useful, link architecture employing binary phase-shift keying (BPSK). This is an example of a BPSK link that incorporates a modest amount of scintillation mitigation. Specifically, this link employs differentially coherent PSK with a provision for coherent I-channel DPSK demodulation (IDPSK) when channel conditions permit. The placement of the differential encoder immediately before the biphase modulator not only enables the use of DPSK demodulation, it also permits the use of interleaving to break up channel error bursts due to slow fading[1]. This in turn makes the use of convolutional encoding and associated error-correction decoding much more effective.

The frequency-shift keyed (FSK) link shown in Figure 3 employs a more extensive arsenal of scintillation mitigation techniques. Not only is noncoherent FSK more robust than PSK in scintillation conditions, this M-ary link layout incorporates two levels of interleaving in conjunction with chip repetition to further mitigate the effects of amplitude fading and phase scintillation. Frequency hopping is also employed, primarily for antijam (AJ) protection. The use of frequency-hopped FSK (FH/FSK) modulation can, under certain circumstances, provide some diversity gain in frequency selective scintillation as a side benefit.

----

[1] If differential encoding is performed prior to error-correction encoding, as is often done in a conventional coherent PSK link, interleaving cannot be used. Because of the π-radian phase ambiguity inherent in coherent BPSK demodulation, polarity reversals caused by phase slips would be scrambled by the deinterleaver, rendering the error-correction decoder completely useless. In the configuration of Figure 2, however, phase ambiguities are resolved within the demodulator prior to deinterleaving, allowing the decoder to function properly.

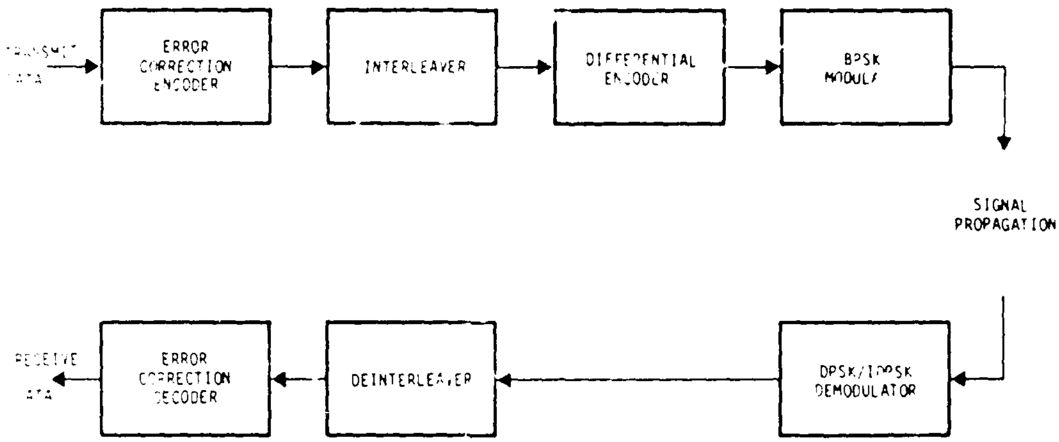

Figure 2. A simple PSK link layout.

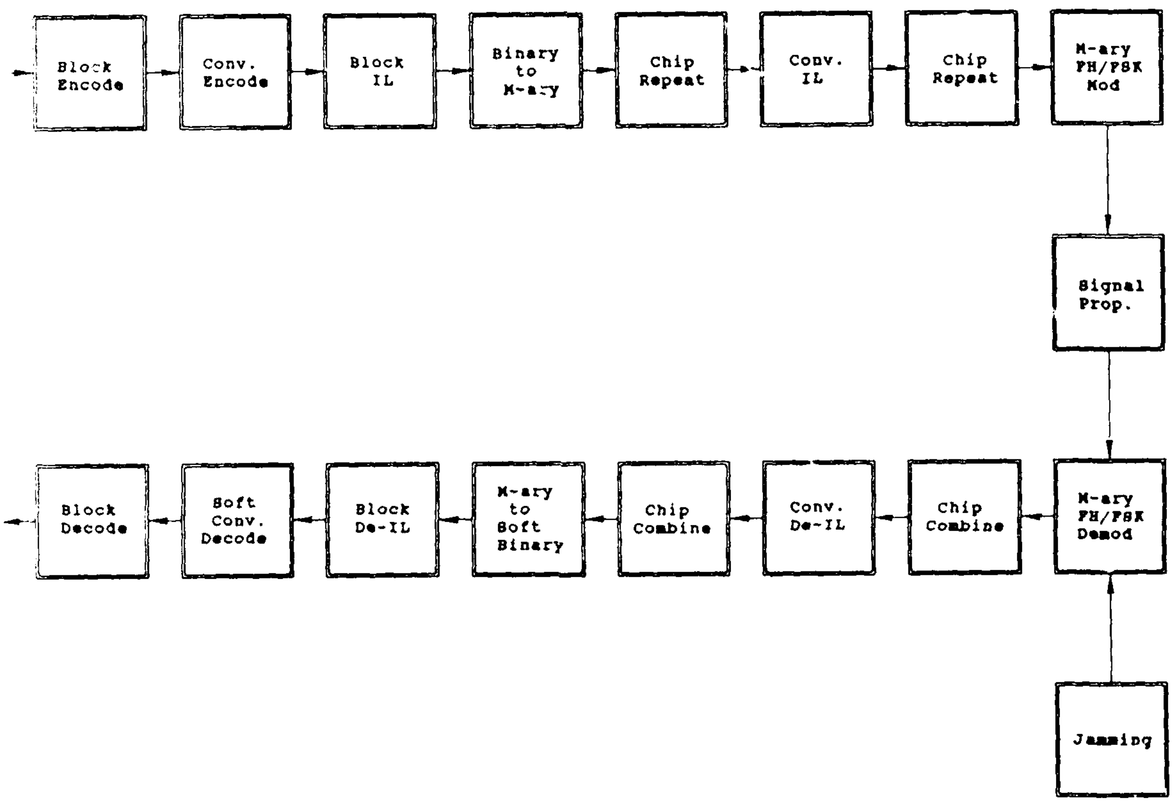

Figure 3. A more complex FSK link layout.

The principal point being made here by the layouts in Figures 2 and 3 is that there can be a large variation in the functional arrangement of links that may have to operate in fading channels. The CAD software architecture should readily accommodate such functional variations.

To further highlight this point, consider the architectural requirements imposed by the link layouts shown in Figures 4 and 5. These are additional variations of M-ary FSK links employing coding, interleaving, repetition, and frequency hopping to provide both scintillation mitigation and AJ protection. The variations here involve different types of error-correction codes and different methods of performing chip repetition. The configuration shown in Figure 5 employs an interesting use of a binary code that is matched to the M-ary FSK modulation alphabet. The code rate is chosen such that each branch of the code tree exactly equals one modulation symbol. This facilitates using the M-ary FSK matched filter outputs directly as symbol metrics in a maximum-likelihood Viterbi decoder.

Now consider an FH/FSK link that employs unmodulated synchronization symbols (or *sync chips*) for purposes of time and frequency tracking. In a typical design wherein sync chips are employed, data and sync chips are organized into blocks or frames, with specific numbers of each type of chip contained in each frame. To minimize degradation due to pulse jamming or other sources of periodic interference, the arrangement of data and sync chips is often permuted pseudorandomly from one frame to another.

With the addition of sync chips, the symbol and chip rates through the various functional elements can become quite complex. For the purposes of illustration, assume a 75 b/s 8-ary FSK link employing rate 1/2 error-correction coding and 24-chip repetition. Without sync chips, the symbol rate starts at 75 b/s, increases to 150 b/s at the encoder output, drops to 50 symbols/s at the output of the binary-to-octal converter, and then increases to 1200 chips/s with the factor of 24 repetition through the channel. Now, assume that 2 sync chips are added to each 14 data chips to form a 16-chip frame. While the maximum *data* chip rate remains at 1200 chips/s, the *total* channel chip rate increases to 1371.43 chips/s. There is no requirement for data rates to be integers, and this example is not uncommon. Because such designs are of considerable practical interest, with the number of sync chips and data chips per frame being design variables (together with code rates and all of the other parameters), the CAD program architecture must be capable of adapting to the requirements of such link designs.

A software architecture has been developed that readily accommodates all of the link configurations shown here, as well as many other variations. This is an *interrupt-driven* architecture, similar to that which is used in real-time software for microprocessor-based modems. The interrupt-driven architecture was developed for use in detailed sampled-data software simulations of various types of modems, and it has proven extremely useful in that application, readily adapting to a widely diverse set of link designs with no program modifications and no "do loops" needed. A form of this architecture is expected to prove useful in the CAD program as well.

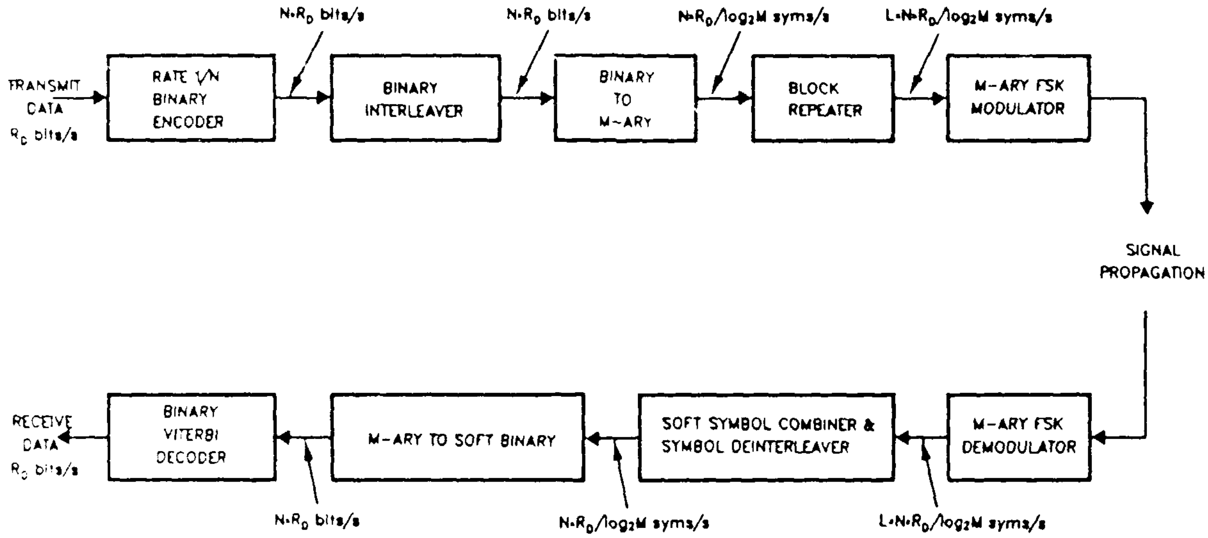

Figure 4. M-ary FSK link with arbitrary binary code.

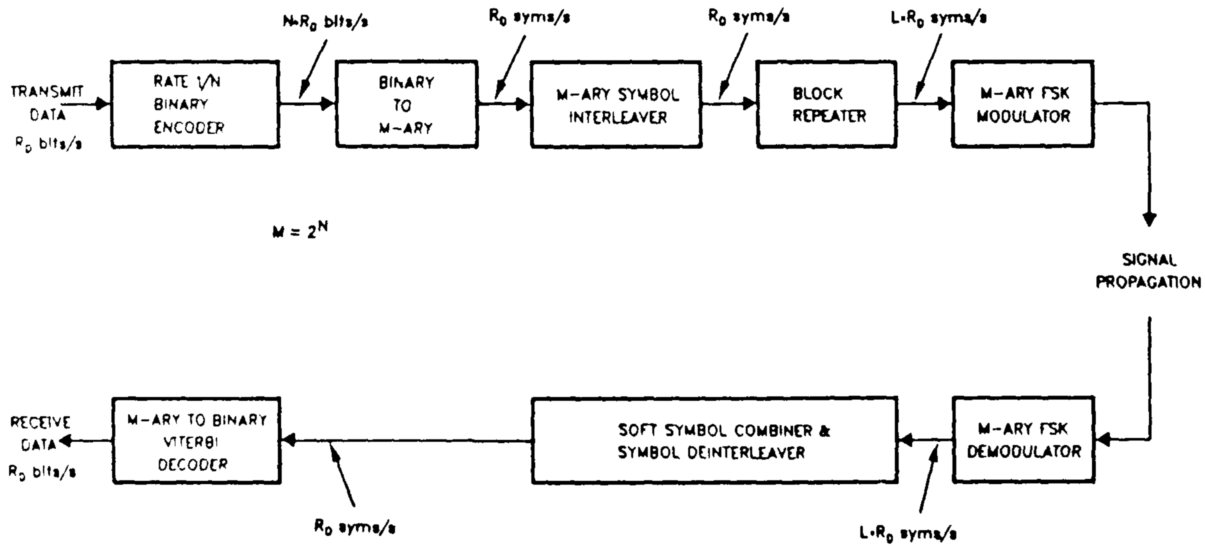

Figure 5. M-ary FSK link with matched binary code.

2.2 CAD ALGORITHMS.

Definition of the algorithms needed to automate the design of digital communications links, given performance requirements, design constraints, and signal specification data, has been greatly facilitated by use of results of previous research. Much of this research has been accomplished by the Mission Research Corporation for the Defense Nuclear Agency, the Air Force Weapons Laboratory, the Air Force Space Systems Division, and other Government and industrial organizations. Examples of relevant research efforts are provided by the references listed at the end of this report.

The fading channel first affects a communications link in the receiver demodulator, where the signal is detected and the imposed data modulation is estimated. The receiver includes such functions as automatic gain control (AGC), automatic frequency control (AFC) with frequency-lock loops (FLL), bit timing synchronization with delay-lock loops (DLL), carrier phase synchronization with phase-lock loops (PLL), data detection and quantization, deinterleaving or diversity combining, and error-correction decoding. The detailed design configurations and design parameter values involved in implementing these receiver functions significantly affect the performance of the link in the presence of signal scintillation disturbances.

Much relevant information concerning selection of modulation and coding design parameters to mitigate signal scintillation is given by Bogusch [*1987*]. As discussed there, the minimum value of the signal decorrelation time limits the minimum channel bit rate that can be employed with conventional digital modulation and demodulation techniques. The minimum value of the frequency selective bandwidth limits the maximum channel bit rate that can be employed with conventional signal processing techniques. The maximum value of the decorrelation time influences the selection of error-correction coding and diversity parameters, including interleaver dimensions, code type and decoder design. The minimum spatial decorrelation distance (or maximum angular scattering variance) limits the useful aperture size of conventional antennas. The maximum decorrelation distance affects spatial diversity requirements. Quantitative relationships between these and other signal parameters and the affected system design parameters have been established. These relationships have been used to define the requirements for the CAD algorithms.

Additional information on scintillation mitigation techniques, as well as information on the design of robust tracking loops, has been developed and presented by Bogusch, et al. [*1981, 1983*], Dana, et al. [*1982, 1986*], Guigliano, Michelet, Newman [*1983*], Sawyer, et al. [*1981, 1984*], and Wittwer [*1979, 1980, 1982*], to name a few. Results from these and other relevant sources will be used to complete the development of the CAD algorithms in the subsequent phase of this effort.

These previous efforts have demonstrated that the most accurate method of determining the performance of a digital communications system is by means of detailed simulation of the various elements comprising the system. An extensive inventory of simulation modules have been developed, tested, and applied in the design and evaluation of numerous existing and planned systems.

While the simulation approach, involving both software simulations and hardware channel simulators, remains the most accurate method of relating channel parameters to link performance, the CAD software requires algorithms that execute in less time. The time constraints result from the fact that the design process typically involves many tradeoffs, each of which must be evaluated over a range of signal-to-noise ratios, decorrelation times, and frequency selective bandwidths. Although any of the specific data points could be generated easily using available simulation models, the accumulation of data required to optimize the selection of design parameters would involve many simulation runs. This is not objectionable in a batch mode environment, but would involve lengthy sessions in front of a computer screen in an interactive environment.

Consequently, the CAD algorithms give rise to a requirement for rapid execution, while at the same time requiring considerable fidelity. Fortunately, a solution to these seemingly contradictory requirements has been developed during this Phase I effort. We shall use the term *transfer functions* to describe the type of algorithms that will satisfy the requirements imposed by the CAD package.

A transfer function is simply a method of characterizing the output of a given element in terms of its input. If the functional elements of a digital communications link were all linear devices, it would be possible to derive such transfer functions analytically. Most of the functional elements in modern digital communications systems are nonlinear, however, precluding direct analytical solution. Here is where the extensive background in simulating such elements proves extremely valuable. The previous research efforts cited above have resulted in the accumulation of enough simulation data that we can define the required transfer functions empirically.

Consider first the heart of a digital link, the demodulator. The transfer function of a digital demodulator may be defined as the output error rate (channel bit error rate) as a function of the input signal-to-noise ratio (channel bit energy-to-noise density ratio, E_{cb}/N_0), channel decorrelation time (τ_0) , and channel frequency selective bandwidth (f_0) . Figures 6 and 7 provide examples of transfer functions measured in flat ($f_0 \rightarrow \infty$) fading for coherent BPSK and for coherent offset quaternary PSK (OQPSK). The different curves in these figures show the effect of different channel decorrelation times on the demodulator transfer function for the case where the noise bandwidth of the carrier phase tracking loop is set at one-thirtieth of the channel bit rate (*i.e.*, $B_L = T_{cb}^{-1}/30$, where T_{cb} is the channel bit period). Figures 8 and 9 provide similar examples for differentially coherent QPSK and differentially coherent BPSK, respectively, which do not require phase tracking loops.

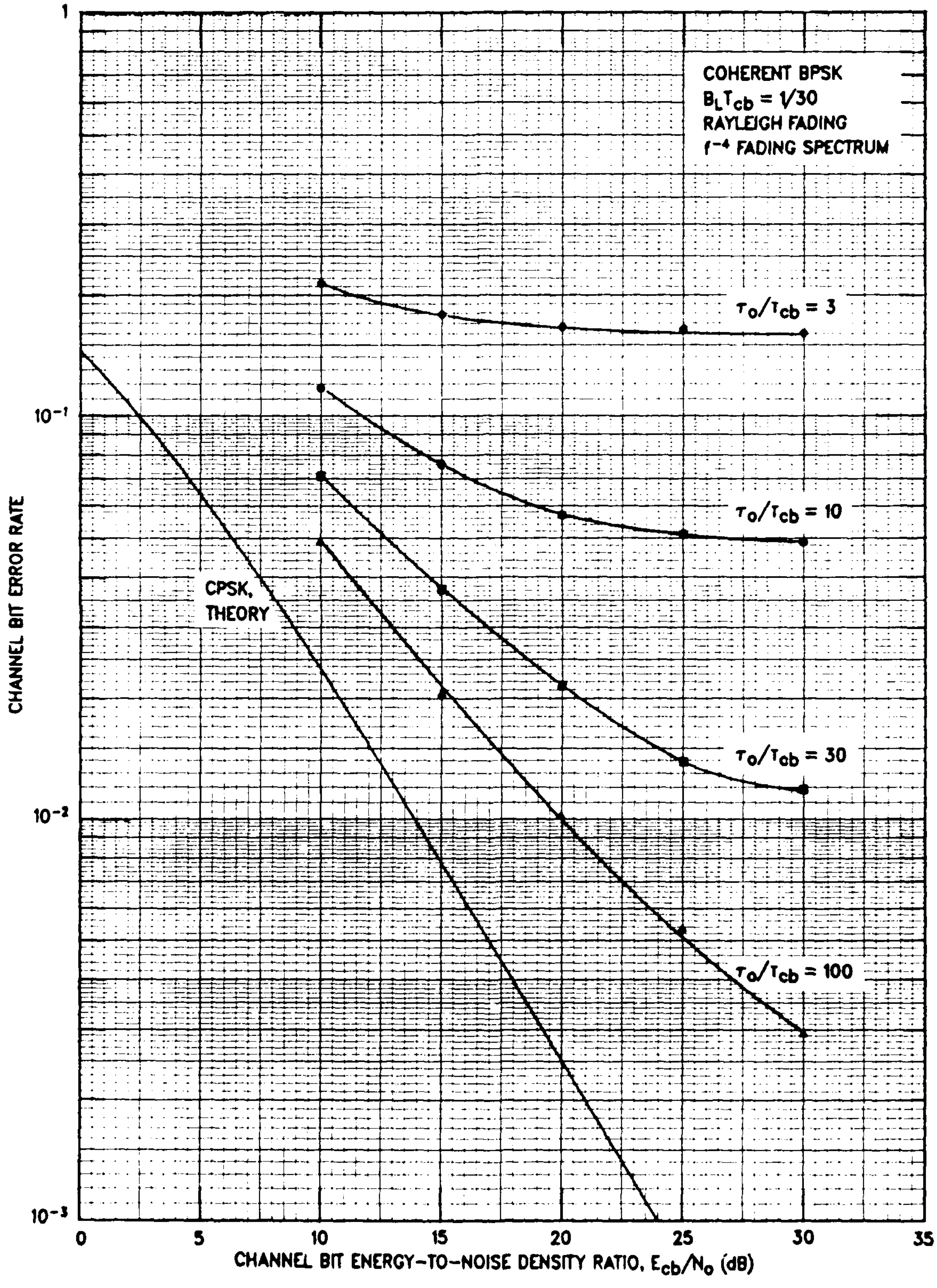

Figure 6. Transfer function for coherent BPSK demodulator.

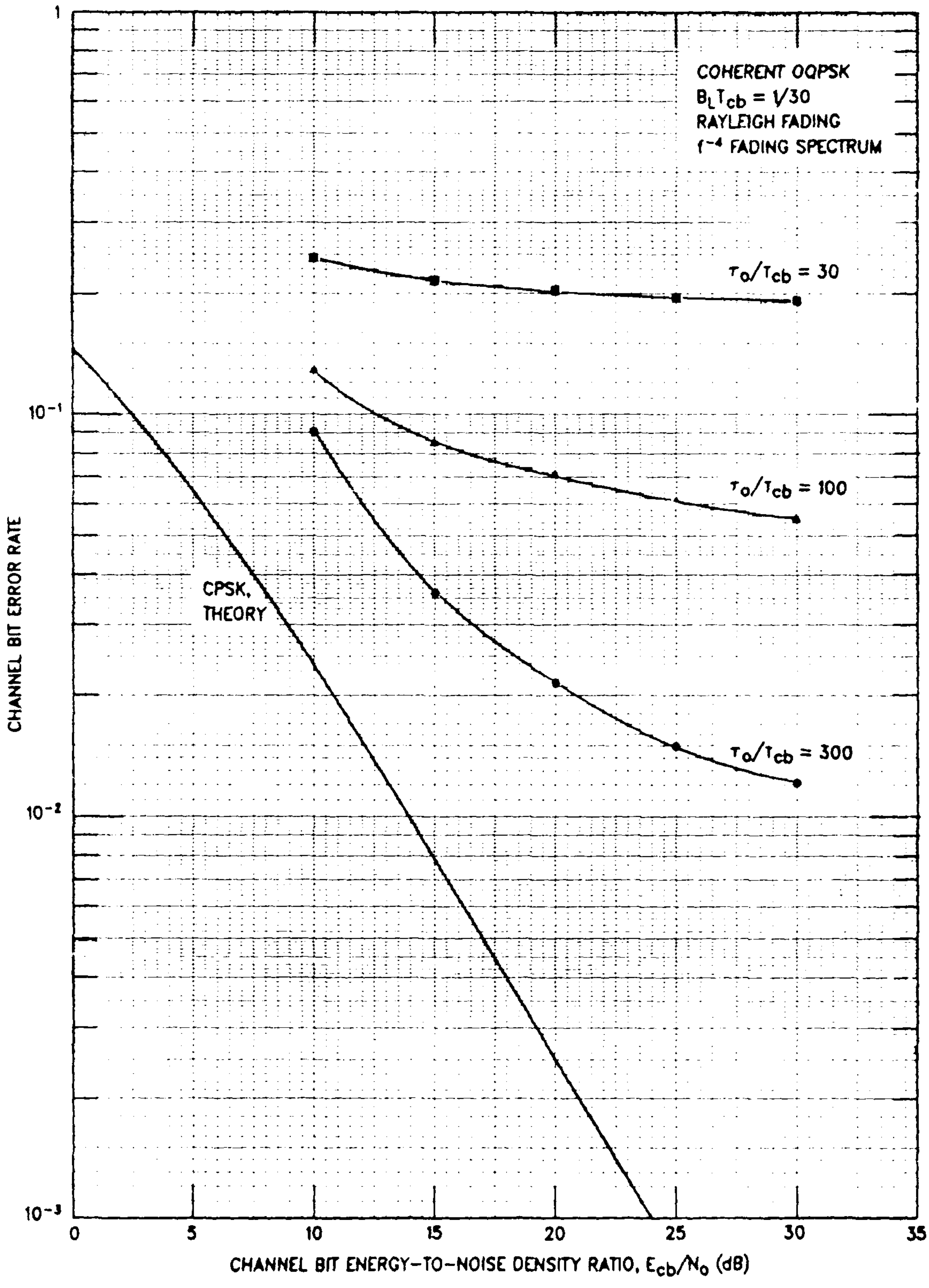

Figure 7. Transfer function for coherent offset QPSK demodulator.

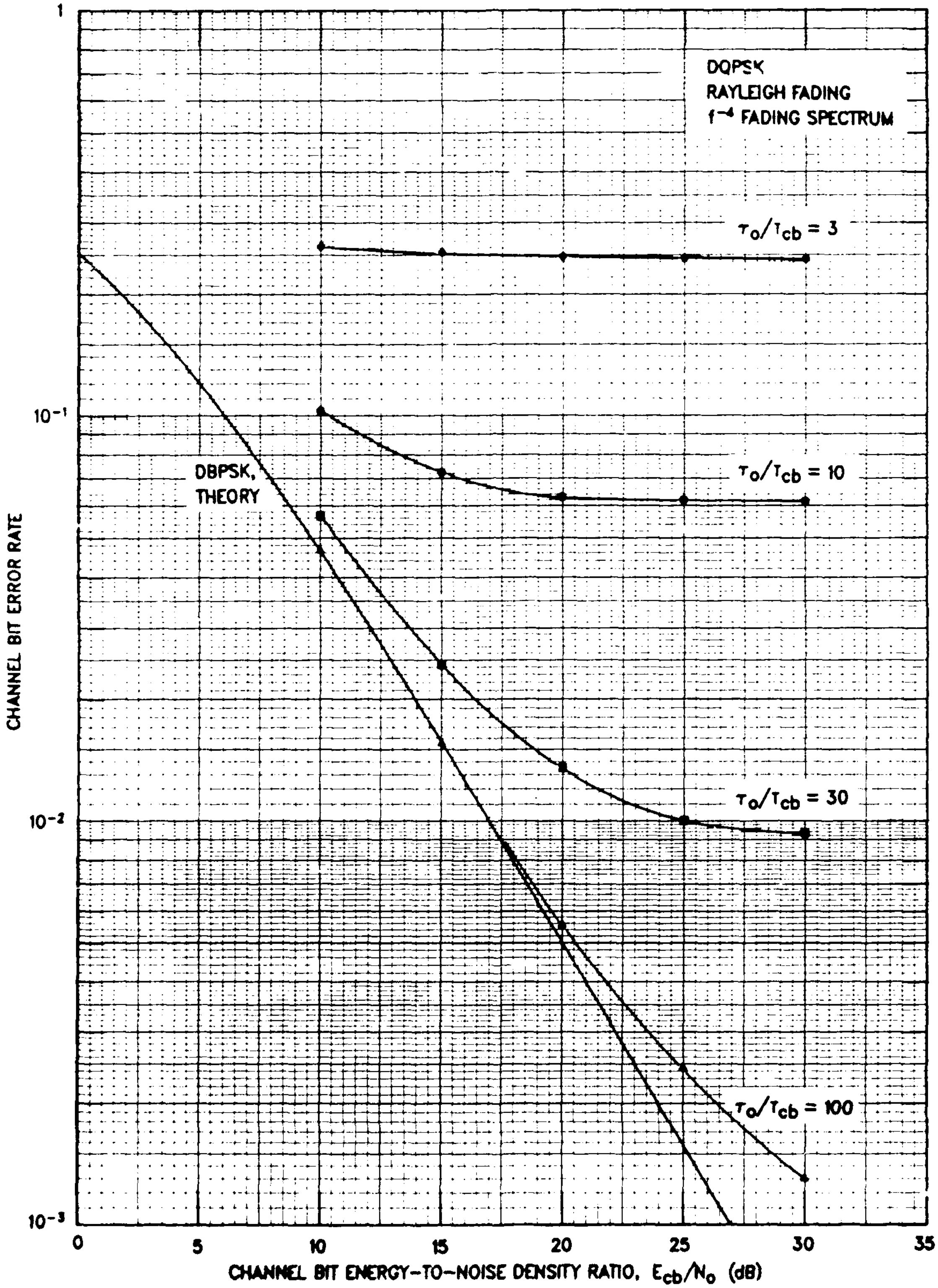

Figure 8. Transfer function for differentially coherent QPSK demodulator.

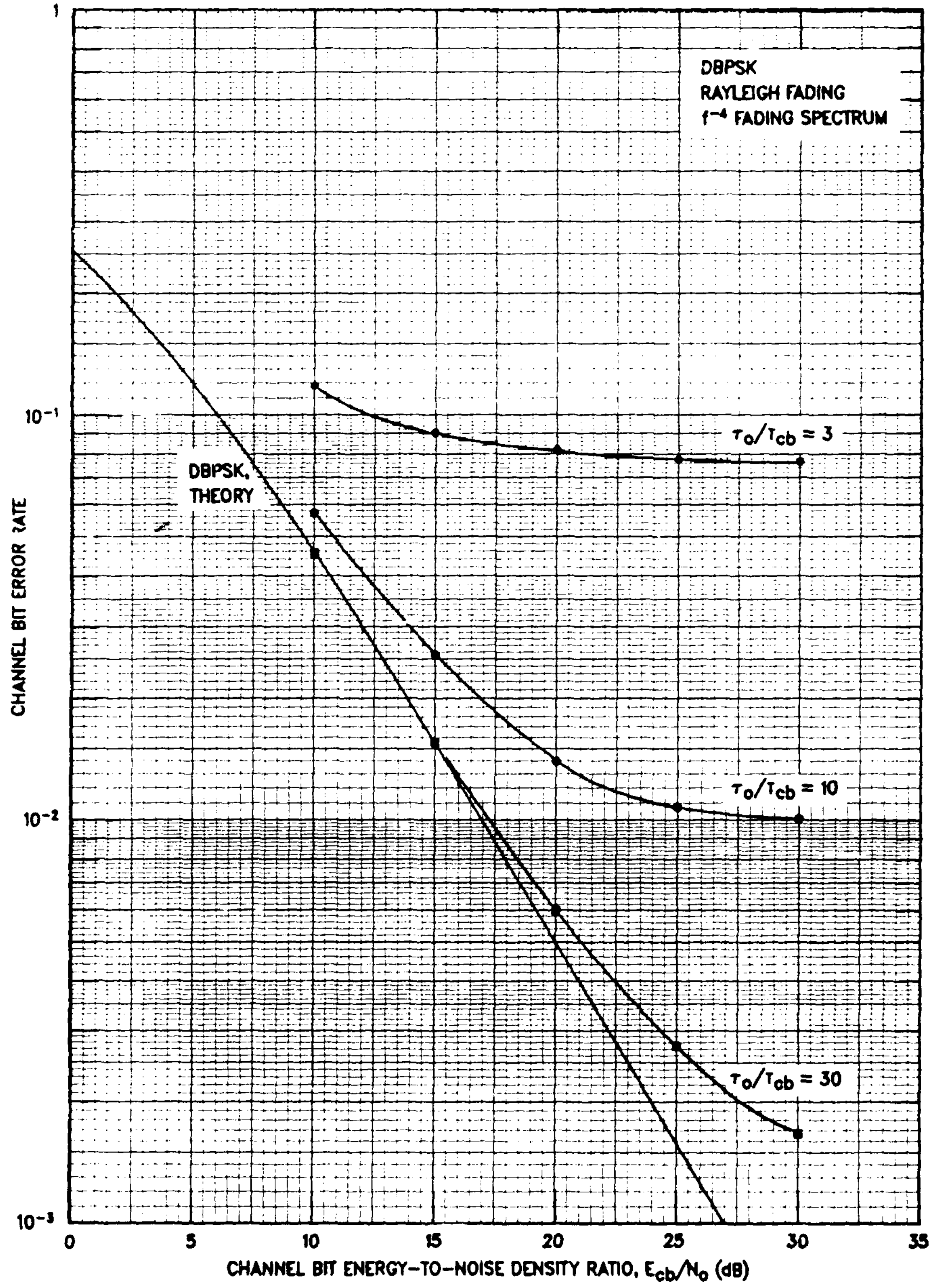

Figure 9. Transfer function for differentially coherent BPSK demodulator.

Corresponding results for several noncoherent FSK demodulators are given in Figures 10 through 13. These four figures provide the transfer functions for binary FSK, quaternary FSK, 8-ary FSK, and 16-ary FSK, respectively. These figures are for the case where the FSK modulation tone spacing (Δf) is set at the minimum value for orthogonal signaling. The minimum orthogonal tone spacing is equal to the modulation symbol rate, which is the reciprocal of the modulation symbol period (*i.e.*, $\Delta f = 1/T$, where $T = [\log_2 M] \cdot T_{cb}$). This is a common choice to minimize the signaling bandwidth. However, it is not necessarily the best choice, particularly in a fast fading channel where larger tone spacings can yield significantly better performance. The effect of increased tone spacing on the 8-ary FSK transfer function is shown in Figure 14. This figure shows the improvement obtained in fast fading with factors of 3 and 10 increase in tone spacing.

Note that the dependence on decorrelation time in Figures 6 through 13 is given parametrically in terms of the ratio of channel decorrelation time to channel bit period (τ_0/T_{cb}). This parametric approach to the empirical definition of the required transfer functions enables a large amount of data to be condensed into a relatively small volume, and facilitates interpolation and extrapolation to values not explicitly contained in the transfer function data base.

These demodulator transfer functions are appropriate when the transmission rate has been defined, and the performance of the link is to be evaluated. Perhaps the designer has not yet specified the data rate, or perhaps the data rate is given but the code rate and number of chip repetitions have yet to be defined. Then the CAD algorithms should provide the user with guidance as to appropriate choices of modulation rates (and hence code rates and repetition factors) for the various modulation options. This type of information is provided by the data plotted in Figure 15. This figure shows the <u>required</u> signal-to-noise ratio needed to achieve a usable channel bit error rate as a function of channel bit rate for several types of demodulators. The channel bit rate is normalized here by the channel decorrelation time. These data show that there is a minimum usable channel bit rate for each type of demodulator. This, together with the specified user data rate, defines the effective code rate that must be incorporated to allow the demodulator to operate with relatively low signal-to-noise ratio near its slow fade limit (toward the right side of the figure).

Once the code rate has been established, evaluation of the link design can proceed to the next step. This involves definition of the error-correction decoder performance, which again can be formulated in the CAD algorithms by means of a transfer function. Figure 16 provides an example of the measured transfer function for a popular rate 1/2, constraint length 7 convolutional code with maximum-likelihood Viterbi decoding. Because the previous design step was aimed at eliminating any vulnerability to fast fading, the measurements here are made in a slow Rayleigh-fading channel, where the amount of interleaving is crucially important to the effectiveness of the decoder. Thus, the measured transfer functions in Figure 16 are defined in terms of the relative interleaver span, *viz.*, the ratio of interleaver time span to decorrelation time (T_{IL}/τ_0).

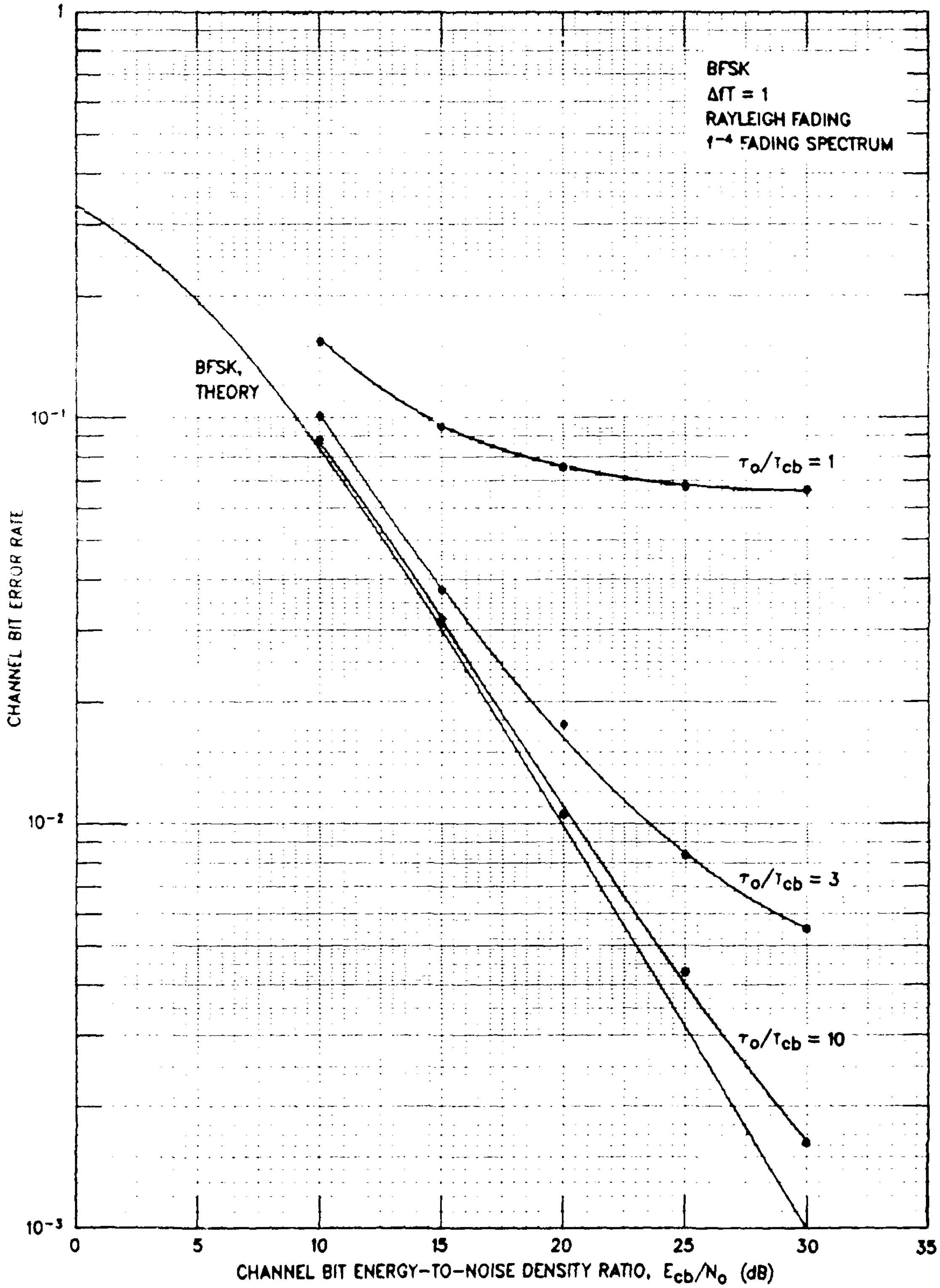

Figure 10. Transfer function for binary FSK demodulator.

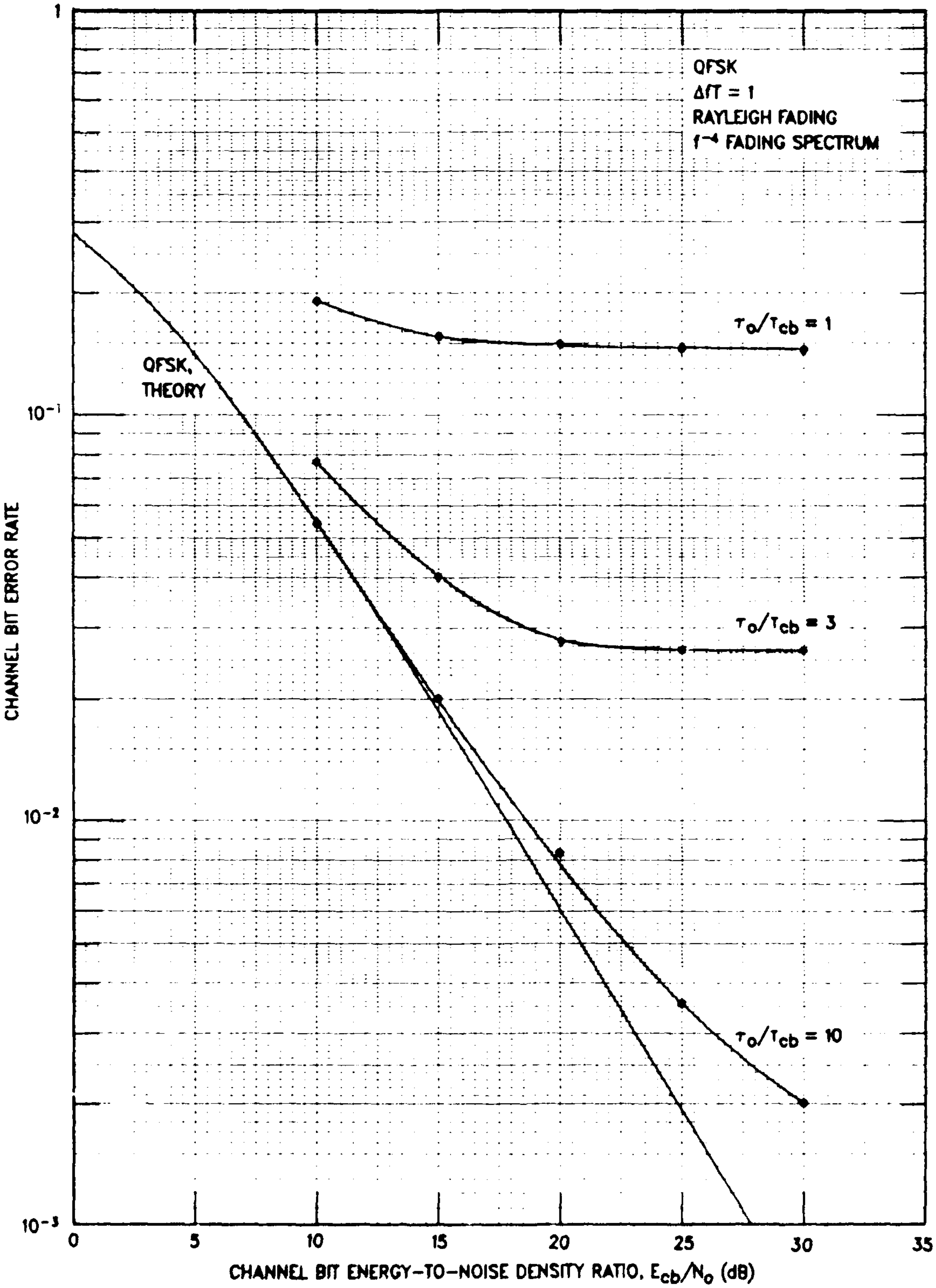

Figure 11. Transfer function for quaternary FSK demodulator.

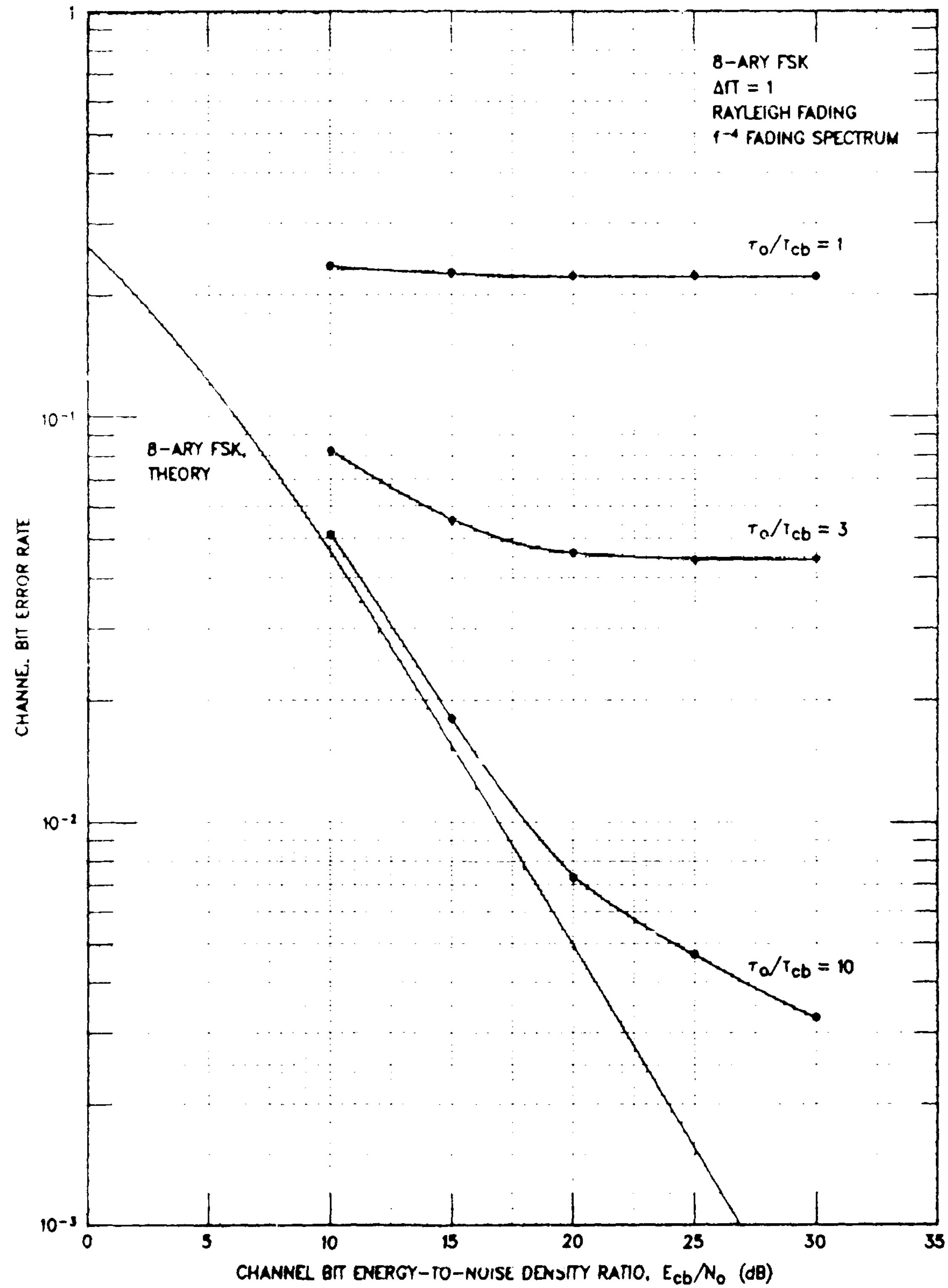

Figure 12. Transfer function for 8-ary FSK demodulator.

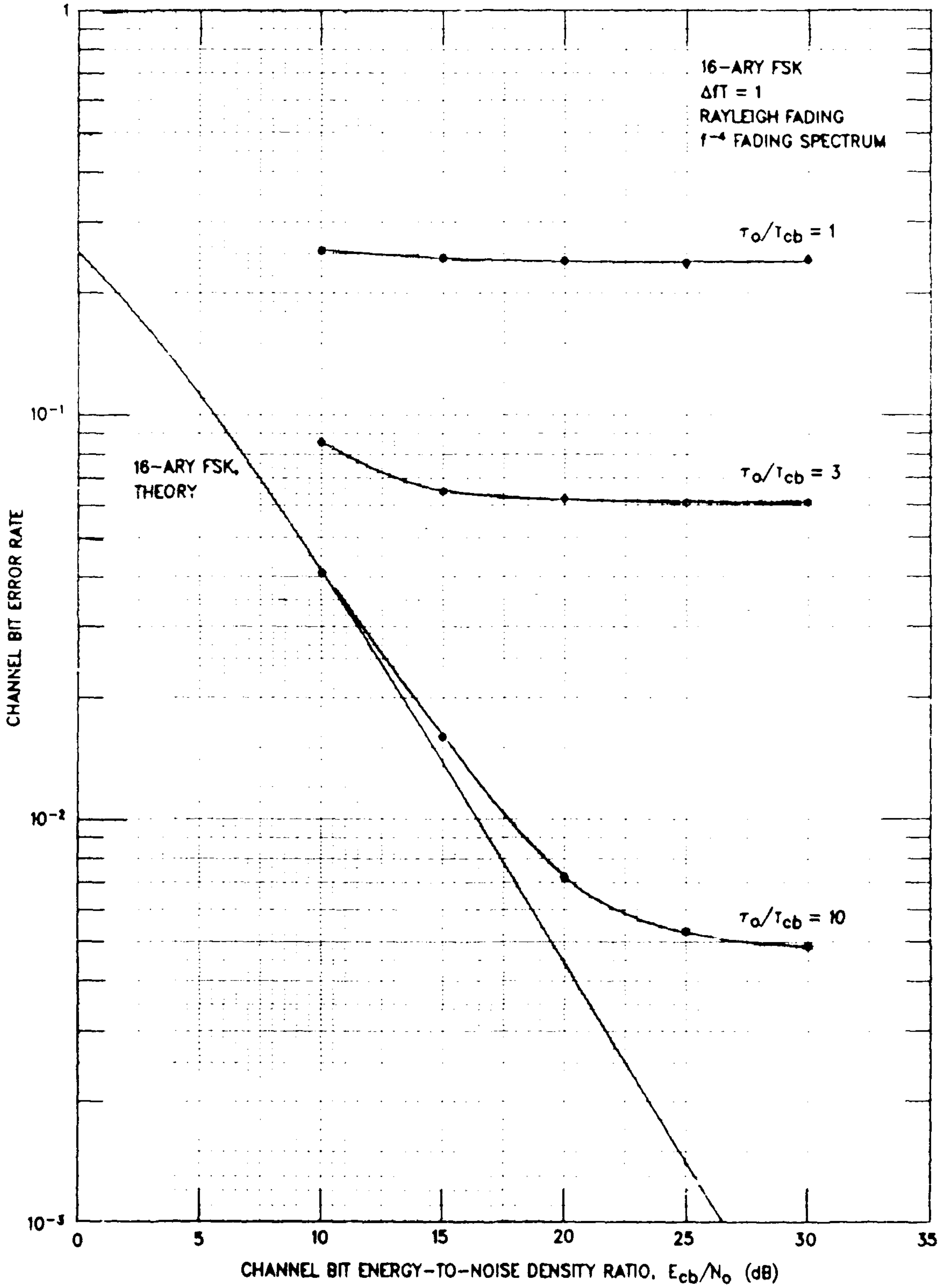

Figure 13. Transfer function for 16-ary FSK demodulator.

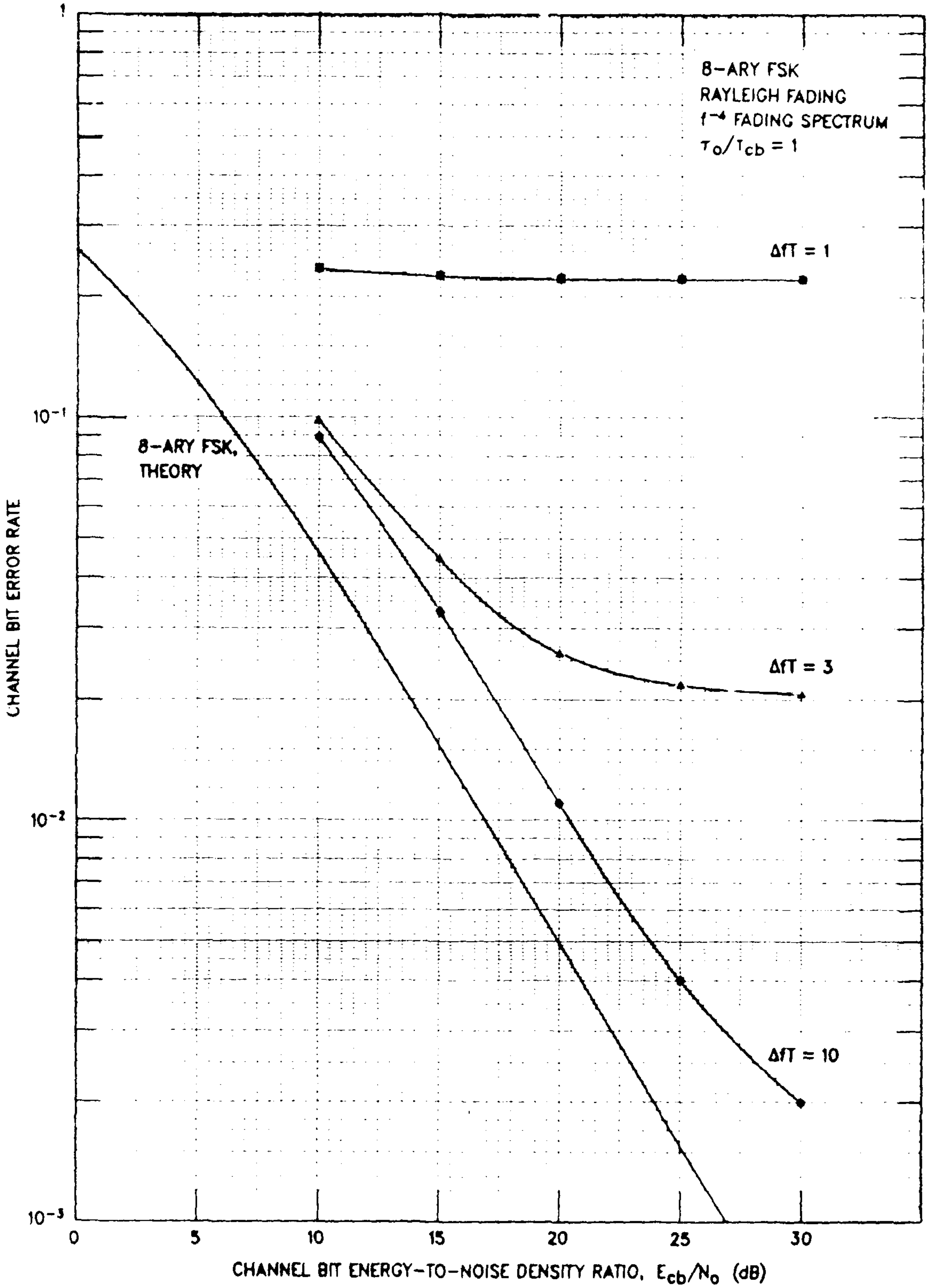

Figure 14. Effect of tone spacing on 8-ary FSK transfer function.

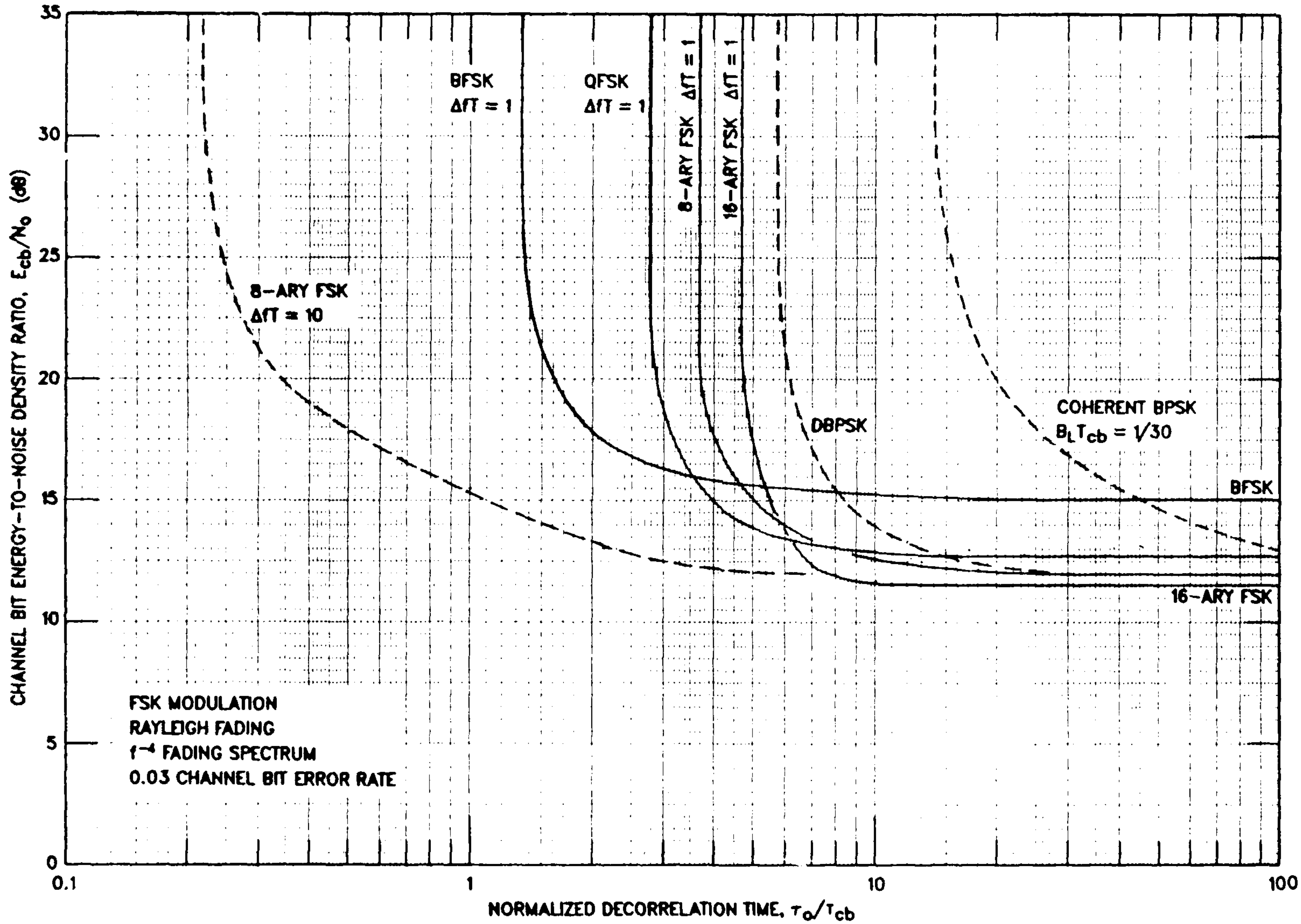

Figure 15. Minimum channel bit rates for FSK and PSK demodulators.

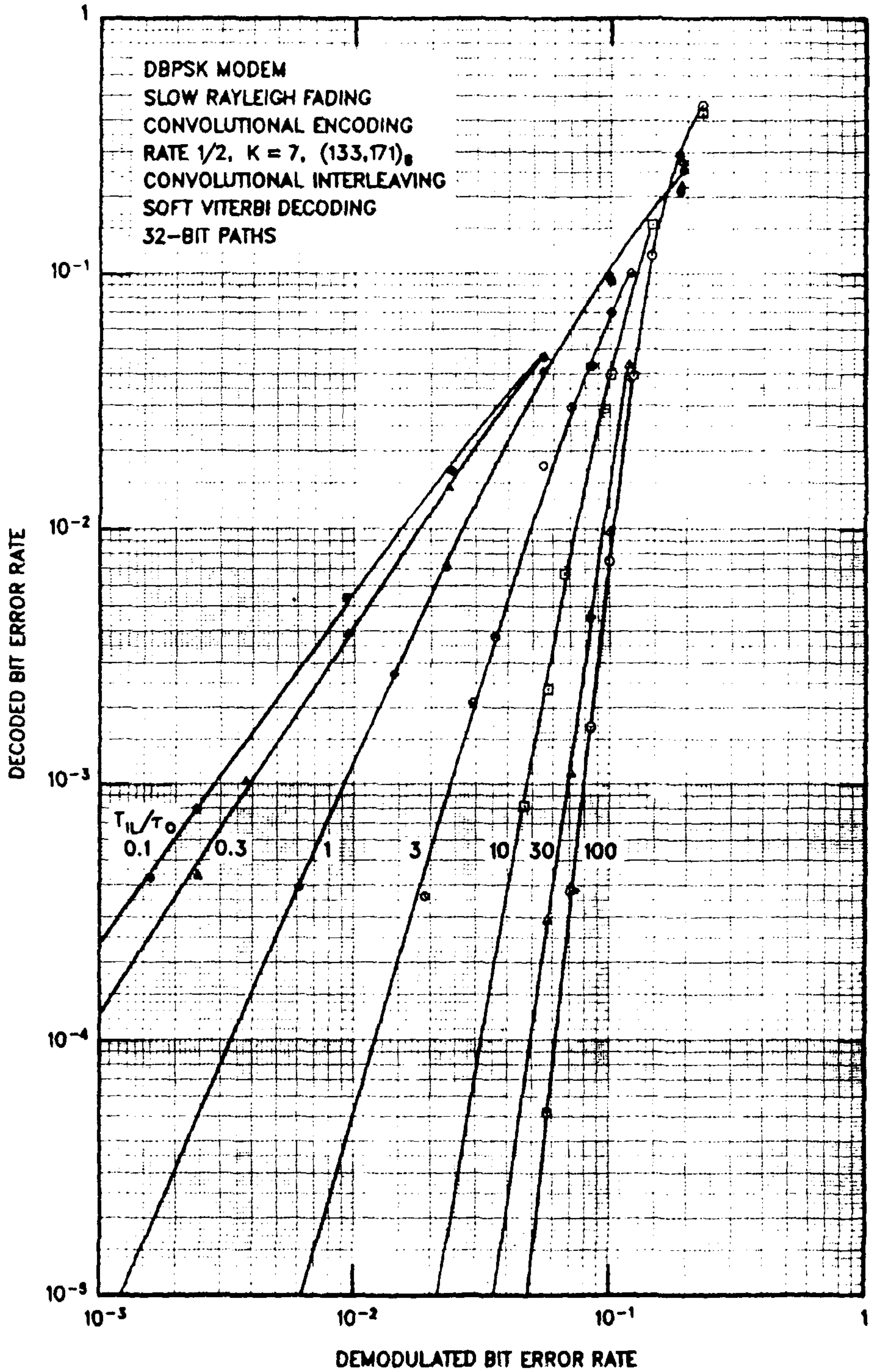

Figure 16. Transfer function for rate 1/2 Viterbi decoder.

The interleaver time span is equal to the effective amount of interleaver memory (symbol span) divided by the rate at which symbols are fed into the interleaver. For example, the symbol span of a row-column (block) interleaver is equal to the product of the number of rows and number of columns. Similar definitions apply to synchronous and convolutional interleavers. Figure 16 shows that in a Rayleigh-fading channel large interleavers lead to increased decoder effectiveness, resulting in low output decoded bit error rates being obtained with relatively large input demodulated bit error rates.

Because an important step in the process of survivable link design is selection of an appropriate code rate, transfer functions will be included in the CAD software for a range of useful code rates. The effect of code rate on the decoder transfer function is illustrated in Figure 17. This figure is for the case of a fairly large interleaver having a span of 100 times the channel decorrelation time.

While maximum-likelihood (Viterbi) decoding is optimum, it is generally most useful in conjunction with relatively short constraint length convolutional codes. Sometimes a designer may wish to investigate longer code constraint lengths, which usually require the use of other, non-optimum, types of decoders. Figure 18 shows an example of the transfer function for a specific feedback decoder. Transfer functions for two Viterbi decoders are included in Figure 18 for comparison. The CAD software will thus be able to properly evaluate a number of different types of codes and decoders for use in fading channels.

Perhaps an overall code rate has been determined, and the question then turns to the options for implementing that rate in a link. As an example, consider a 75 b/s link in which binary DPSK is being evaluated as a possible modulation/demodulation technique. For purposes of illustration, assume that the link is intended to operate in fast fading channels where τ_0 is one millisecond. From the algorithm represented by Figure 15 it is determined that the ratio τ_0/T_{cb} should not be less than about 10 for DBPSK. *Since the minimum* value of τ_0 is specified, the *maximum* value of T_{cb} can be determined. In the present example, it is seen that T_{cb} should not exceed 10^{-4} seconds, corresponding to a channel bit rate not less than 10 kb/s. Given the 75 b/s user data rate, it is apparent that the effective code rate must be around 1/134 or less. The question now is, what is the most efficient way of implementing such a low rate code?

One method of achieving a low rate code is to employ a conventional code of, say, rate 1/3 or 1/8 in conjunction with symbol repetition. In this example, a repetition factor around 17 to 45 or more would be needed in conjunction with a rate 1/8 code and a rate 1/3 code, respectively. To evaluate the tradeoffs involved here, a transfer function for the repetition and combining function is needed in the CAD algorithms. Such a transfer function can be derived from the results plotted in Figure 19. This figure shows the amount of noncoherent combining loss that results from symbol repetition in both AWGN and Rayleigh fading channels over the range from no repetition to a repetition factor of 300.

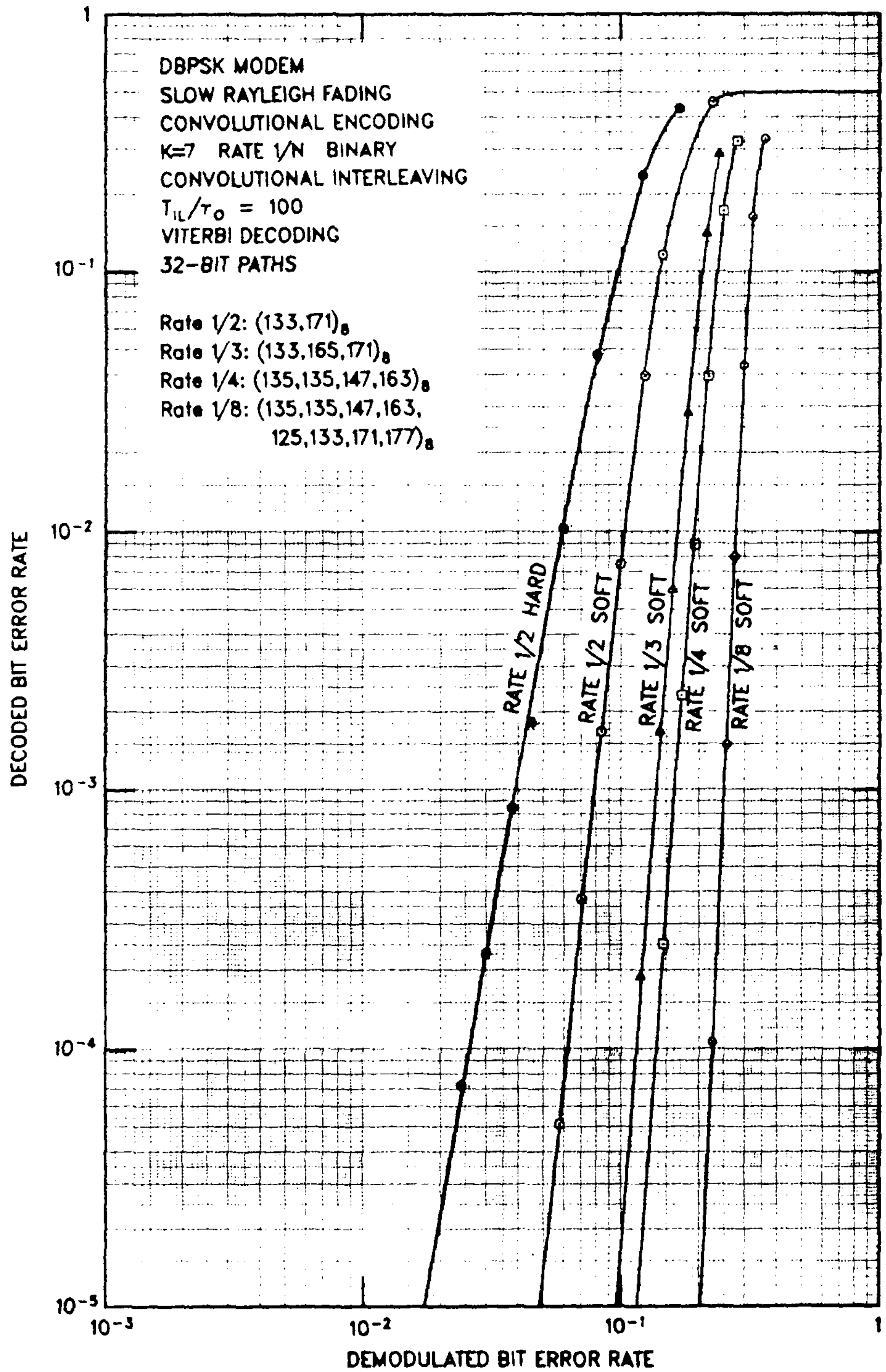

Figure 17. Effect of code rate on decoder transfer function.

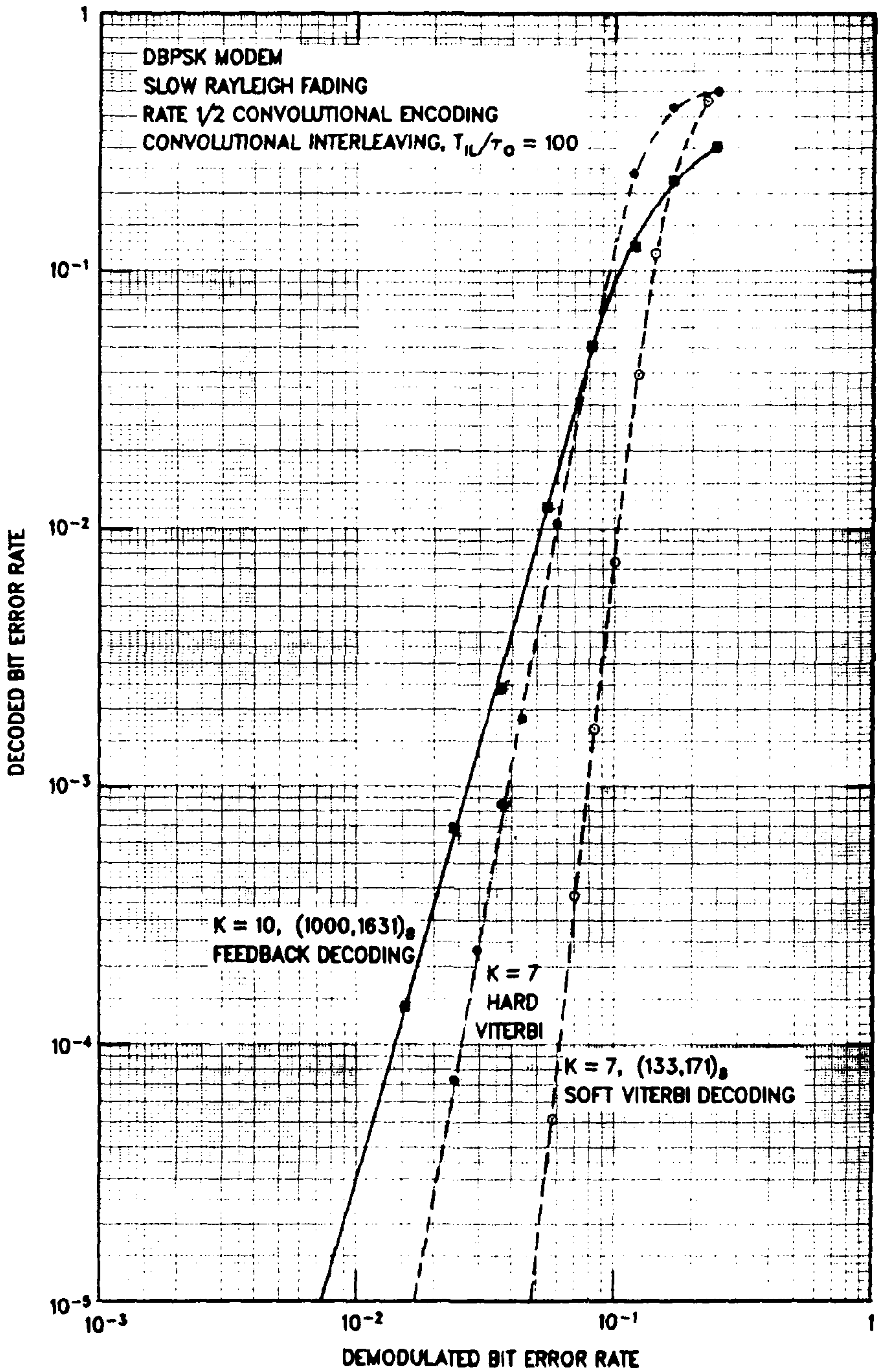

Figure 18. Effect of decoder design on transfer function.

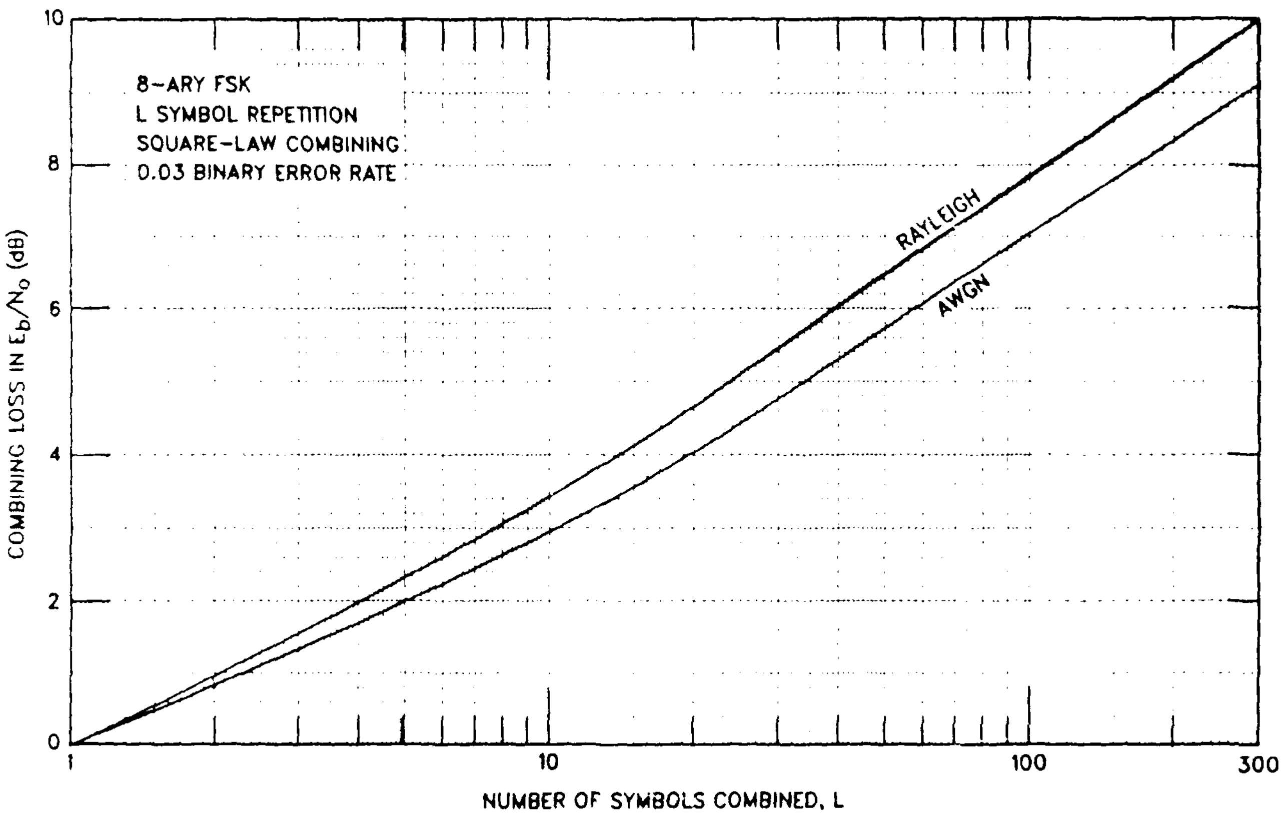

Figure 19. Transfer function for noncoherent combining.

This transfer function approach can be used to represent each of the functional elements of a digital communications link within the CAD software. The advantage of this approach, in addition to computational efficiency, is that the functional elements can be arranged and rearranged in the link layout just as they could be if they were explicitly simulated. Of course, the transfer function approach requires that each element to be included in the CAD software be explicitly simulated beforehand. As noted previously, a significant amount of simulation data have already been accumulated as a by-product of previous efforts. The remaining data that will be needed to flesh out the CAD algorithms will be generated via simulations during the course of the next phase of this work.

SECTION 3
USER INTERFACE

3.1 USER INPUTS.

An important part of this initial development effort, crucial to achieving a useful product, is the definition of a truly user-friendly interface for the CAD package. The user interface handles all of the interactive data input and output requirements for the package. This includes user specification of overall link configuration and any known constraints on the link design, such as data rate, carrier frequency, nominal maximum value of carrier-power-to-noise density ratio, etc. System parameters that are left unspecified by the user are treated as "free" parameters that can be selected by the program to optimize the design.

Another category of user inputs consists of the specifications of ranges of disturbed signal parameter values that the link should be designed to withstand in an operational nuclear environment. These parameters include signal scintillation decorrelation time (τ_0), frequency selective bandwidth (f_0), angular scattering variance ($\sigma_\theta{}^2$), total electron content (TEC), and absorption along the propagation path. User inputs may also include velocities or vehicle dynamics profiles for the terminals at both ends of the link.

The user interface is being designed with a combination of pop-up windows, menus, on-line help and graphics as appropriate to facilitate the input of data and the display of results. The design objective is to make the CAD package easy to use while providing quantitative answers to complex design questions concerning the mitigation of signal scintillation disturbances in a nuclear environment. All interactive communication with the package will be accomplished using standard keyboard and display equipment normally associated with the host processors defined in the following section. Results will be written to the monitor screen and to either a disk file or to a printer, including commonly available dot matrix printers.

Interactive user input will be performed using graphical layouts on the monitor screen, together with keyboard or mouse input. A preliminary design of some of the screen layouts has evolved during this effort. It is envisioned that the main input screen will consist of a functional layout of the communications link, as defined by the user. The user will initially be presented with a menu of communications functions, or blocks, that can be incorporated into the link. As each block is selected, the menu presents a choice of valid functions that can be incorporated at the next point in the link. At each step, the user is prompted with a set of control options with which he can revise blocks already specified, add new blocks, or delete blocks. This graphical link configuration screen thus enables the user to quickly define the functional layout of as much of the communications system as he wishes to specify.

An example of what the link configuration screen might look like, after a user has rather completely defined a link layout, is shown in Figure 20.

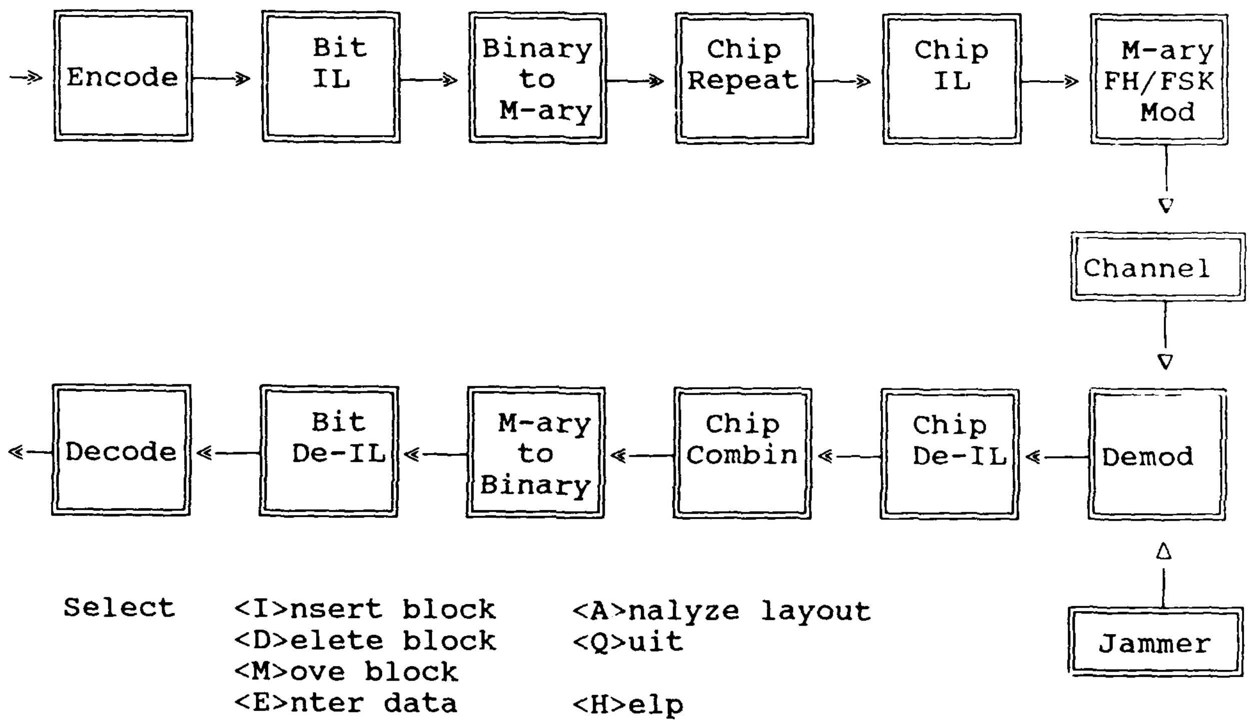

Figure 20. Example of user input screen.

Upon selecting the **Enter data** option from this menu, the user is first queried as to which block he wishes to specify. After moving a screen highlight to identify a particular block, a data selection menu then appears, partially overlaying the link configuration screen. The data selection menu is tailored to the particular communications function for which data is being entered.

For example, if the encoder block is specified, the data selection menu might appear something like the following example in Figure 21.

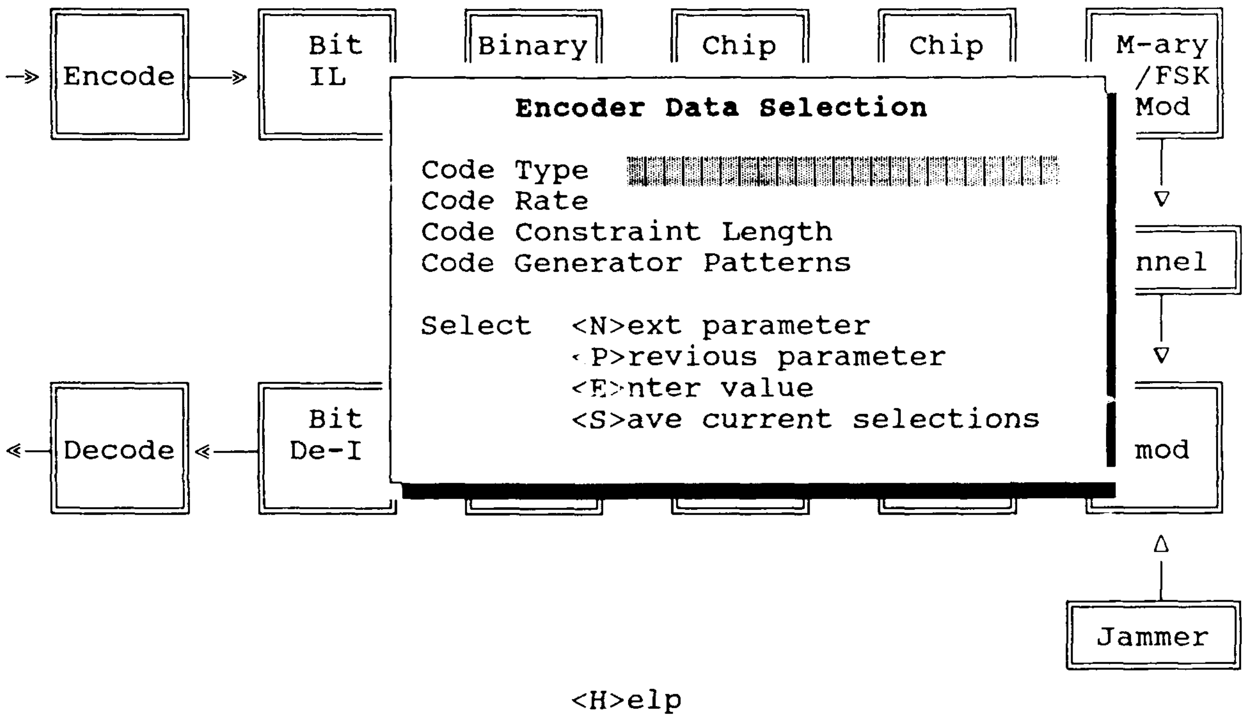

Figure 21. Example of data selection menu.

The user then highlights the parameter he wishes to specify, and enters the value for that parameter. Once he is finished entering values for this parameter block, he saves the selections and returns to the main link configuration menu. Values for the other functional blocks can then be entered in similar fashion, with each block having a parameter menu especially tailored for that function.

At each step of this process, the interface algorithms check the user inputs for appropriateness. If a value is specified that is out of the proper range, or if the function just will not work in the specified place, the user will be informed as to the problem. He will then be prompted as to how to take the appropriate corrective action.

At some point the link will either be rather completely defined, or else the user will have left some design choices unspecified. In either case, when he signals his intention to terminate the initial specification phase, the program will evaluate the likely performance of the link over the specified ranges of signal parameters. These signal parameters (τ_0, f_0, etc.) will have been entered in the **Channel Data Selection** menu, which is one of the data entry menus. If the user has not specified the channel parameters, he will be prompted to enter his choices, or else some rather stressing default values will be used. A *help screen* will be available to the user at this point to assist him, principally by referring him to the *DNA Reasonable Worst-Case Signal Specification* document.

Help screens will be available to assist the user at each step of the link layout and parameter specification process. These screens will provide context-sensitive help that is dependent on what the user is attempting to do at the time that he requests assistance. Thus, the help screens will offer suggestions and guidance tailored to the operation or function currently being performed.

Once the communications link has been defined as much as the user wishes, the CAD program executes the algorithms that evaluate the performance of the link. Development of these algorithms constitutes a major part of this program. As has been described in the preceding section, implementation of the CAD algorithms is based on table look-up functions together with curve fits for interpolation and extrapolation of data. The algorithms are designed to rapidly provide reasonable estimates of link performance over the specified ranges of propagation channel conditions. The algorithms are also being formulated so as to identify those design elements that are found to limit link performance. The CAD program will then provide information on design tradeoffs that may improve performance.

3.2 OUTPUTS.

The results of the algorithmic evaluation of the link will be displayed graphically on the user's monitor screen. Figure 22 provides an example of the type of graphical display that the CAD program is being designed to produce. This figure compares four different link designs, and shows the user how well he is doing relative to an uncoded link and to a link operating in an ideal undisturbed AWGN channel.

Figure 23 shows an example of the manner in which design tradeoff information will be provided to the user. This example compares the bit error-rate performance of three different methods of incorporating an effective code rate of one-eighth into a given link. Two of the options employ a rate 1/2 convolutional code with a factor of four repeat, with the difference between these two options centering around the manner in which the repetition function is implemented. The third option, which is shown to be preferable in terms of performance, is to employ a well-chosen rate 1/8 convolutional code with no additional repetition.

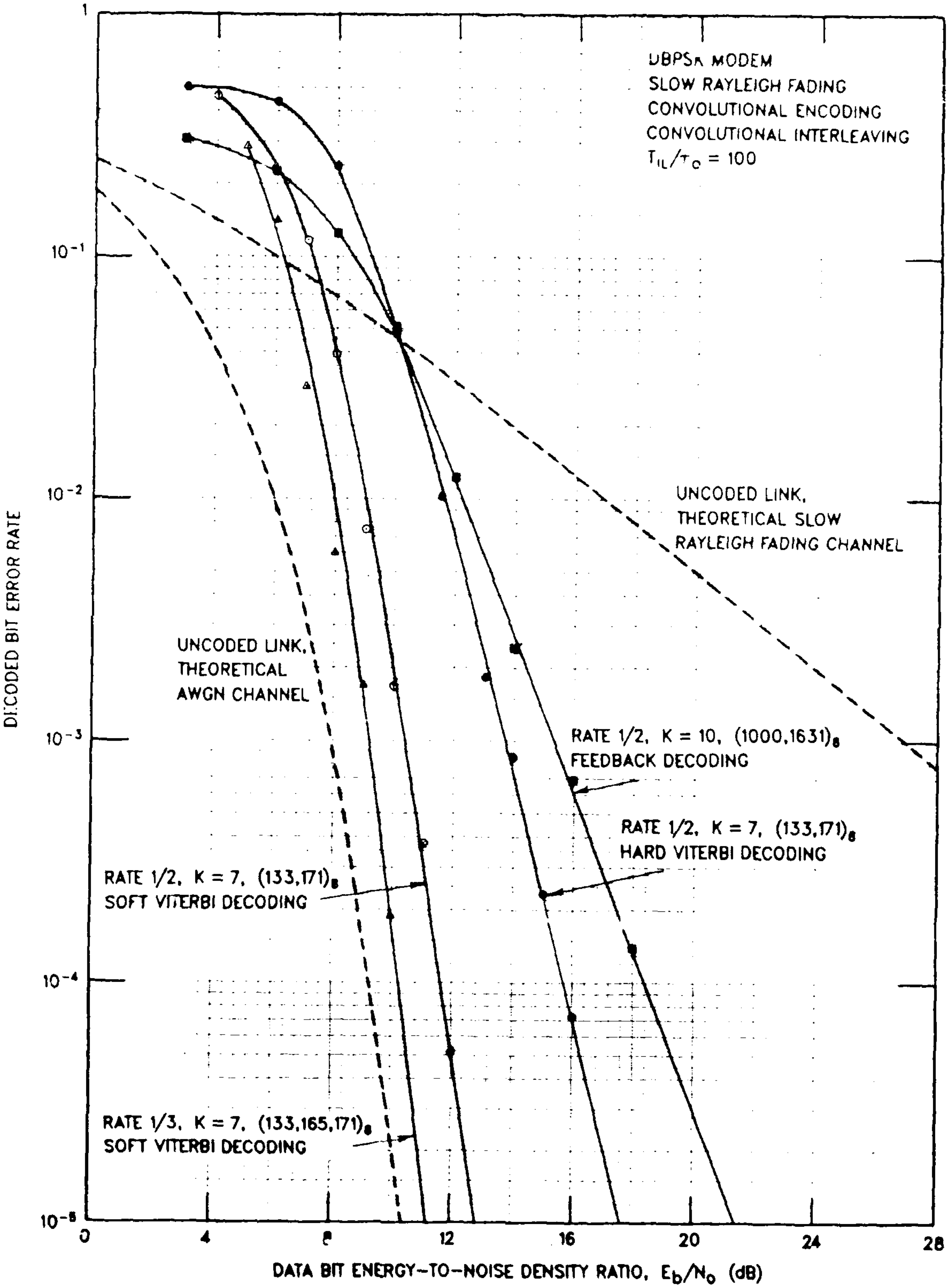

Figure 22. Prototype of link evaluation results screen.

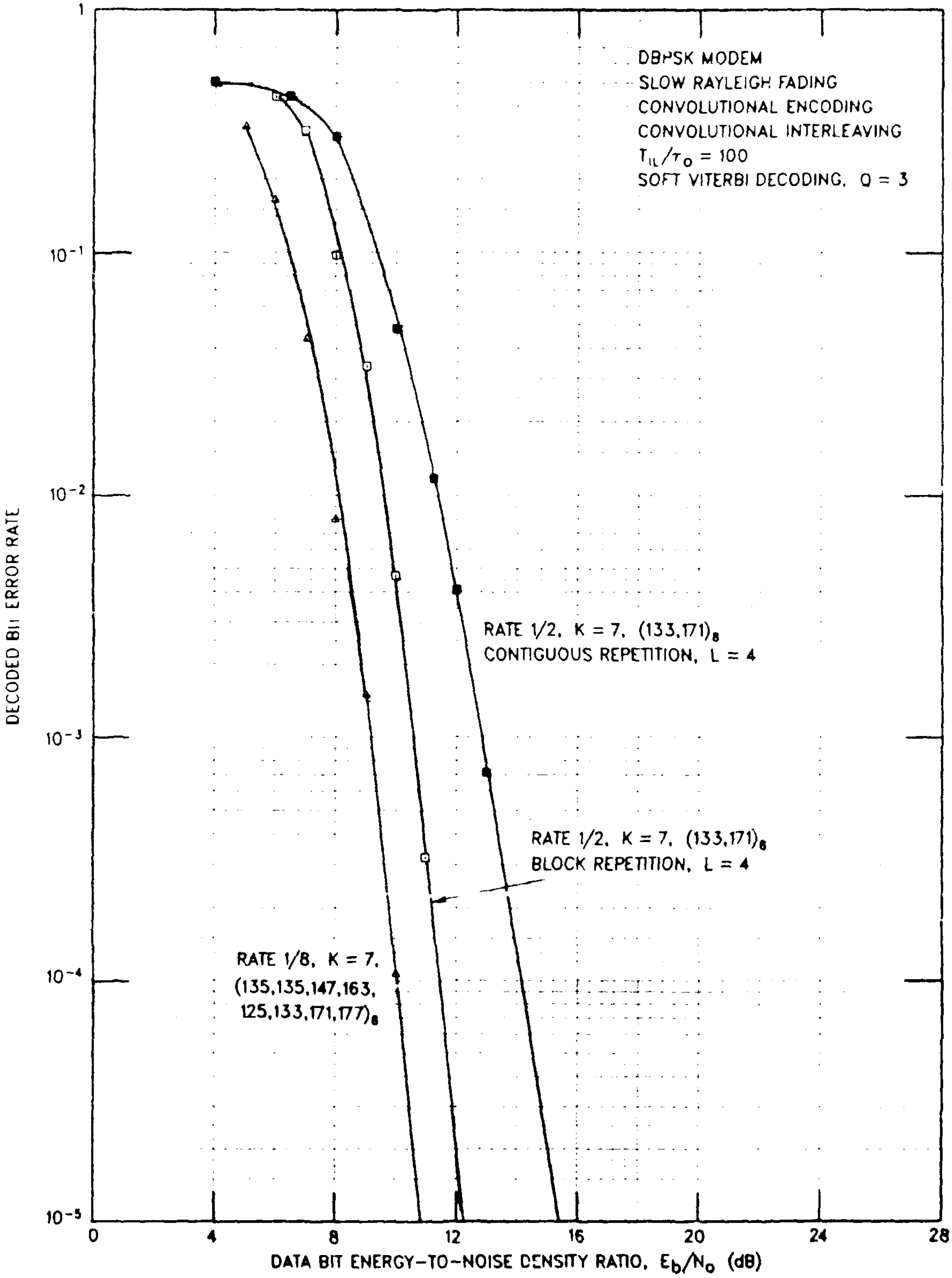

Figure 23. Example of design tradeoff information.

SECTION 4
HOST PROCESSORS

4.1 INTEL 8086 PROCESSOR FAMILY.

To provide a baseline for the implementation of the CAD package, two families of desktop computers are adopted as nominal standards to host the software. Together, they constitute a sizable installed hardware base, one that will make the CAD application software quite useful in a variety of system design tasks.

The first of these hosts is typified by an IBM PC-AT-compatible machine with an Intel 80286 processor operating at a clock speed of 8 MHz or higher, and having an Intel 80287 numeric coprocessor. The PC-AT is assumed to have at least 512 kilobytes (kB) of random-access memory (RAM), a hard disk with at least 20 megabytes (MB) of capacity, and a single floppy disk drive with at least 360 kB capacity. This configuration is commonly encountered (or exceeded) in both government and industrial facilities. Indeed, many AT-compatible machines have at least 1 MB of RAM and a hard disk with at least 30 MB capacity. Almost all such machines have 1.2 MB floppy drives. Many of the newer AT-class machines have clock speeds of 10 Mhz to 20 Mhz, which provides a significant speed advantage when using computationally-intensive software.

The requirements of the CAD algorithms are compatible with the RAM, disk storage, and processor capabilities of the IBM PC-AT (and 100% compatible machines). This has been determined by constructing a prototype set of link simulation routines that have been installed and run on three different AT-compatible machines. When the CAD software is fully developed, the executable file together with its associated data base is expected to fit within 512 kB of RAM. With the transfer function approach to the CAD algorithms described above, the speed of the Intel 80286 processor in conjunction with an 80287 numeric coprocessor should be quite adequate to achieve a reasonably fast-running package. The use of the 80287 coprocessor, while highly desirable to accelerate the floating-point computations involved in the algorithms, is not an absolute necessity. The CAD package is being designed to run on machines that do not have a numeric coprocessor. However, a noticeable degradation of speed will inevitably accompany such a configuration.

An increasing number of AT-compatible machines available today employ the Intel 80386 processor with an 80387 coprocessor. The CAD package will not only run on such machines, it will run quite rapidly. Even the older PC-XT should be able to run the package, albeit with noticeably decreased speed because of its slower 8088 processor and narrow 8-bit data bus. The use of an 8087 coprocessor will surely be a necessity if the package is to be run on an XT-class machine.

This IBM-compatible family of machines generally operates under the Microsoft Disk Operating System (MS-DOS) or the IBM version of it (PC-DOS).

Consequently, the RAM requirements of the CAD executable code will be sized to fit within the constraints imposed by IBM PC's operating under PC-DOS or MS-DOS. As has been noted, many AT-compatible machines have at least 1 MB of RAM. Here the DOS environment becomes the limiting factor, supporting applications only up to 640 kB of RAM. The CAD package will be sized to fit within this constraint. This should not present any problem because the RAM requirements of the CAD package will probably be around 512 kB.

In summary, the running time of the CAD package is likely to be dictated by a combination of PC processor speed and disk access time. As has been discussed, the CAD package is being designed to run on any standard IBM PC-AT and may be usable on an IBM PC-XT as well. However, the 8-bit bus and slower clock speed of the XT, together with its relatively slow hard disk drive, will undoubtedly lead to noticeable degradation of speed compared to the AT with its 16-bit bus and 8 MHz (or faster) clock. Hence it is anticipated that, within the IBM-compatible host category, most users of the CAD package will employ an AT-class machine having Intel 80286/80287 processors or Intel 80386/80387 processors.

4.2 MOTOROLA 68000 PROCESSOR FAMILY.

The other host family being targeted in this CAD software development is represented by a Macintosh SE or Macintosh II with a Motorola 68020 or 68030 processor. Either of these host machines is assumed to have a hard disk with at least 20 MB of capacity, and a single floppy disk drive with at least 800 kB capacity. These specifications are commonly exceeded, with higher capacity disk drives being the norm. As for the PC host family, it is assumed that there will be at least 512 kB of RAM available for the CAD software.

Thus the requirements of the CAD algorithms are compatible with the RAM, disk storage, and processor capabilities of the Macintosh host family. With the transfer function approach to the CAD algorithms, the speed of the Motorola 68020/68030 processors should be quite adequate. Indeed, those users who run the package on a Macintosh SE or Macintosh II having a 68030 processor should experience the greatest speed advantage. Benchmark tests that have been made with Fortran-coded scientific routines indicate that this class of Macintosh machine can be expected to execute the CAD algorithms approximately three times faster than a 10-MHz 80286 machine with an 8-MHz 80287 coprocessor.

4.3 DOCUMENTATION AND DISTRIBUTION.

The CAD package is being coded in ANSI-standard Fortran. This choice ensures that the coded algorithms will be portable to any computer for which a Fortran compiler is available. This includes the IBM PC family and the Apple Macintosh family of host machines. Also, the use of Fortran will allow the algorithms to be ported to larger minicomputers and mainframes in the event that should prove desirable. The modular architecture being developed for the CAD package will ensure that new results and new mitigation techniques can be readily incorporated as they are developed.

The Ryan-McFarland Fortran compiler has been selected to compile the CAD algorithms for use on IBM-compatible PCs using the Intel processor family running under DOS version 2.1 or higher. This is a GSA-certified ANSI-standard Fortran 77 compiler that makes use of (but does not require) a numeric coprocessor (8087/80287/80387) if it is installed in the PC. Another ANSI-standard Fortran 77 compiler will be used to compile the Macintosh version of the CAD algorithms.

It is planned that documentation of the CAD package will be prepared in two volumes: a *user manual* and a *technical reference manual*. The reason for documenting the package in two volumes is partly for convenience, and partly in recognition of two categories of users.

Most users will fall in the category of needing only the executable code, together with the associated user manual. Distribution of executable code (.exe files) has become the standard accepted method for distributing PC application software. It is recognition of this fact that has prompted the attention to host processors and their characteristics and limitations. The advantages of distributing executable files are twofold: (1) simplicity for the user, who only has to load the program and start using it, and (2) configuration control for the developer, who does not have to contend with users making unauthorized modifications to the source code.

It is anticipated that there will be a second category of users, who will need to have a copy of the source code as well as the executable code. The technical reference manual will be aimed primarily at this user group.

All users will be required to become registered, or licensed, as is currently done with other DNA codes such as SCENARIO and PRPSIM. This requirement is intended to preclude unauthorized distribution of the CAD package, and to discourage unauthorized modifications to the code.

Distribution of the CAD software package will be accomplished by means of floppy diskettes. The IBM (Intel) version of the CAD package will be prepared for distribution on 5.25-inch diskettes. These will be standard double-sided, double-density diskettes with a capacity of 360 kB. The Macintosh (Motorola) version will be prepared for distribution on 3.5-inch diskettes having a capacity of 800 kB.

SECTION 5
CONCLUSIONS AND RECOMMENDATIONS

Heretofore, quantitative evaluation of communications link performance in stressing nuclear environments, and the development of mitigated designs, has relied on use of large mainframe computers or minicomputers. While the basic nuclear phenomenology and detailed signal propagation calculations still require the application of mainframes or minicomputers, design data bases generated by such computers can now be installed on small, desktop personal computers (PCs). Thus software could be written to access the data bases once they are installed on a PC. The concept then naturally evolves of developing PC software to facilitate the formulation of mitigated link designs to provide specified levels of performance under specified ranges of propagation parameters. Advantages of such PC-based application software include ease of access and quick application to specific problems by analysts.

The primary objective of the work described in this report was to investigate the feasibility of developing PC-based software that will make possible this step forward in survivable link design capability. Based upon the results of this initial development effort, it is our conclusion that it is indeed feasible to develop such a computer-aided design software package.

It is recommended that a Phase II effort be launched to complete the development of the CAD software package and initiate its distribution to the user community. The objectives of the second phase of work would be to further define the program architecture, complete the development of the CAD algorithms, refine the user interface, implement the entire software package on both host processor families, and prepare the user manual and technical reference manual. This second phase will culminate in the distribution of the CAD package to the user community.

The CAD software package that will result from this work should be of considerable utility to the Defense Communications Agency and to System Program Offices (SPOs) who have the responsibility for developing survivable communications systems. This design tool will facilitate the incorporation of DNA and NCG signal specifications into system specifications, and will assist the SPOs in evaluating contractor proposals during source selection and subsequent design reviews.

The DNA should find the CAD package useful in facilitating the dissemination and application of DNA signal specifications by SPOs. Furthermore, the CAD package will assist the DNA in determining the impact of new and revised signal specifications on existing or proposed communications systems.

The CAD package may also find commercial application as a tool for use by industry in the design of robust digital communications systems for fading channel operation in both nuclear and natural environments.

SECTION 6
LIST OF REFERENCES

1. Bogusch, R. L., *Digital Communications in Fading Channels: Modulation and Coding,* MRC-R-1043, Mission Research Corporation, 11 March 1987.

2. Bogusch, R. L., M. J. Barrett, D. L. Knepp, and B. E. Sawyer, *Signal Propagation Effects on Selected Satellite Systems,* Unpublished.

3. Bogusch, R. L., *Scintillation Hardening Options for Spread Spectrum Modems,* Unpublished.

4. Bogusch, R. L., F. W. Guigliano, D. L. Knepp, and A. H. Michelet, *Frequency Selective Propagation Effects on Spread-Spectrum Receiver Tracking,* Proc. IEEE, Vol. 69, No. 7, pp. 787-796, July 1981.

5. Bogusch, R. L., D. L. Knepp, M. A. Messier, and F. W. Guigliano, *GPS Advanced Receiver Design Options,* Unpublished.

6. Bogusch, R. L., F. W. Guigliano, and D. L. Knepp, *Frequency-Selective Scintillation Effects and Decision Feedback Equalization in High Data-Rate Satellite Links,* Proc. IEEE, Vol. 71, No. 6, pp. 754-767, June 1983.

7. Dana, R. A., *Temporal Statistics of Scintillation for Satellite Communication and Radar Systems,* DNA-TR-81-129, MRC-R-692, Mission Research Corporation, April 1982.

8. Dana, R. A., *Propagation of RF Signals Through Structured Ionization - Theory and Antenna Aperture Effect Applications,* DNA-TR-86-158, MRC-R-976, Mission Research Corporation, May 1986.

9. Guigliano, F. W., and R. L. Bogusch, *Design and Evaluation of Survivable Links for IONDS,* Unpublished.

10. Michelet, A. H., *A Computer Simulation of Maximum Likelihood Decoding of Convolutionally Encoded Data Propagated Through a Disturbed Medium,* Unpublished.

11. Michelet, A. H., *Performance of Two Spread Spectrum Communication System Designs in Jamming and Scintillation,* Unpublished.

12. Michelet, A. H., *PSK and FSK Modem Performance With Various Convolutional Codes,* Unpublished.

13. Newman, D. D., *Observations of the Nature and Effects of Interleavers in Communications Links,* AFWL-TR-82-125, MRC-R-704, Mission Research Corporation, February 1983.

14. Newman, D. D., D. J. Krueger, F. W. Guigliano, and R. L. Bogusch, *Nuclear Survivability Criteria for Satellite RF Crosslinks,* Unpublished.

15. Sawyer, B. E., *The Performance of Two (16,2) Octal Block Codes in a Simulated Fading Channel,* AFWL-TR-80-68, MRC-R-538, Mission Research Corporation, March 1981.

16. Sawyer, B. E., and D. D. Newman, *A Preliminary Investigation of Concatenated Coding Schemes Utilizing Soft Decision Processing,* DNA 5853T, MRC-R-616, Mission Research Corporation, March 1981.

17. Sawyer, B. E., and J. E. Owen, *A Look-Ahead Decision Feedback Equalizer,* MRC-R-861, Mission Research Corporation, September 1984.

18. Wittwer, L. A., *The Performance of Advanced Frequency Shift Key Modulation Techniques in Scintillated Environments I,* Unpublished.

19. Wittwer, L. A., *The Performance of Advanced Frequency Shift Key Modulation Techniques in Scintillated Environments II,* Unpublished.

20. Wittwer, L. A., *Radio Wave Propagation in Structured Ionization for Satellite Applications,* DNA 5304D, Defense Nuclear Agency, December 1979.

21. Wittwer, L. A., *A Trans-Ionospheric Signal Specification for Satellite C^3 Applications,* DNA 5662D, Defense Nuclear Agency, December 1980.

22. Wittwer, L. A., *Radio Wave Propagation in Structured Ionization for Satellite Applications II,* DNA-IR-82-02, Defense Nuclear Agency, August 1982.

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